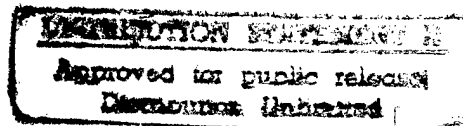




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IMAGING OF MOVING GROUND VEHICLES

FINAL TECHNICAL REPORT



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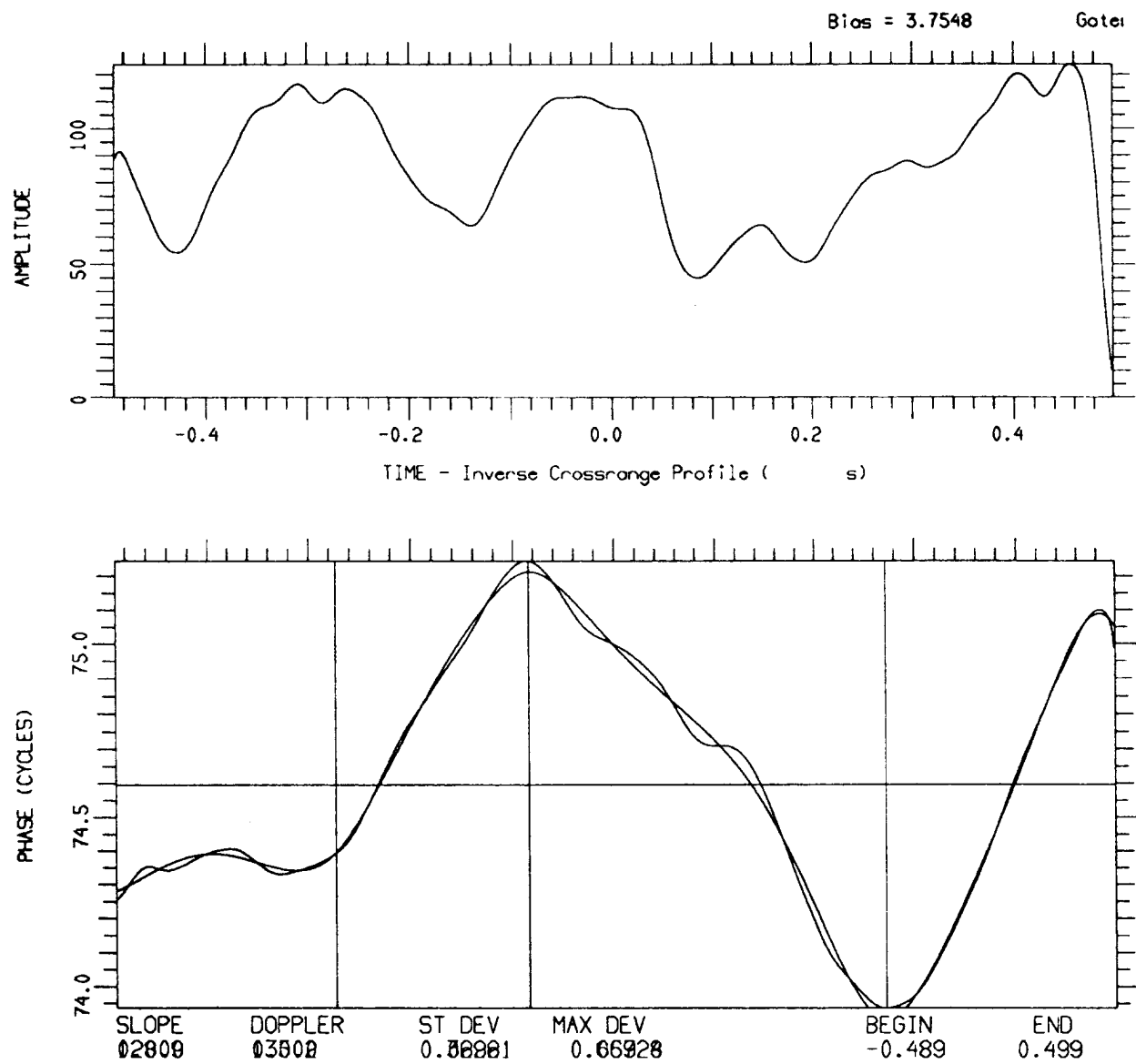


Figure 4.6. Phase Function Spline Fit.

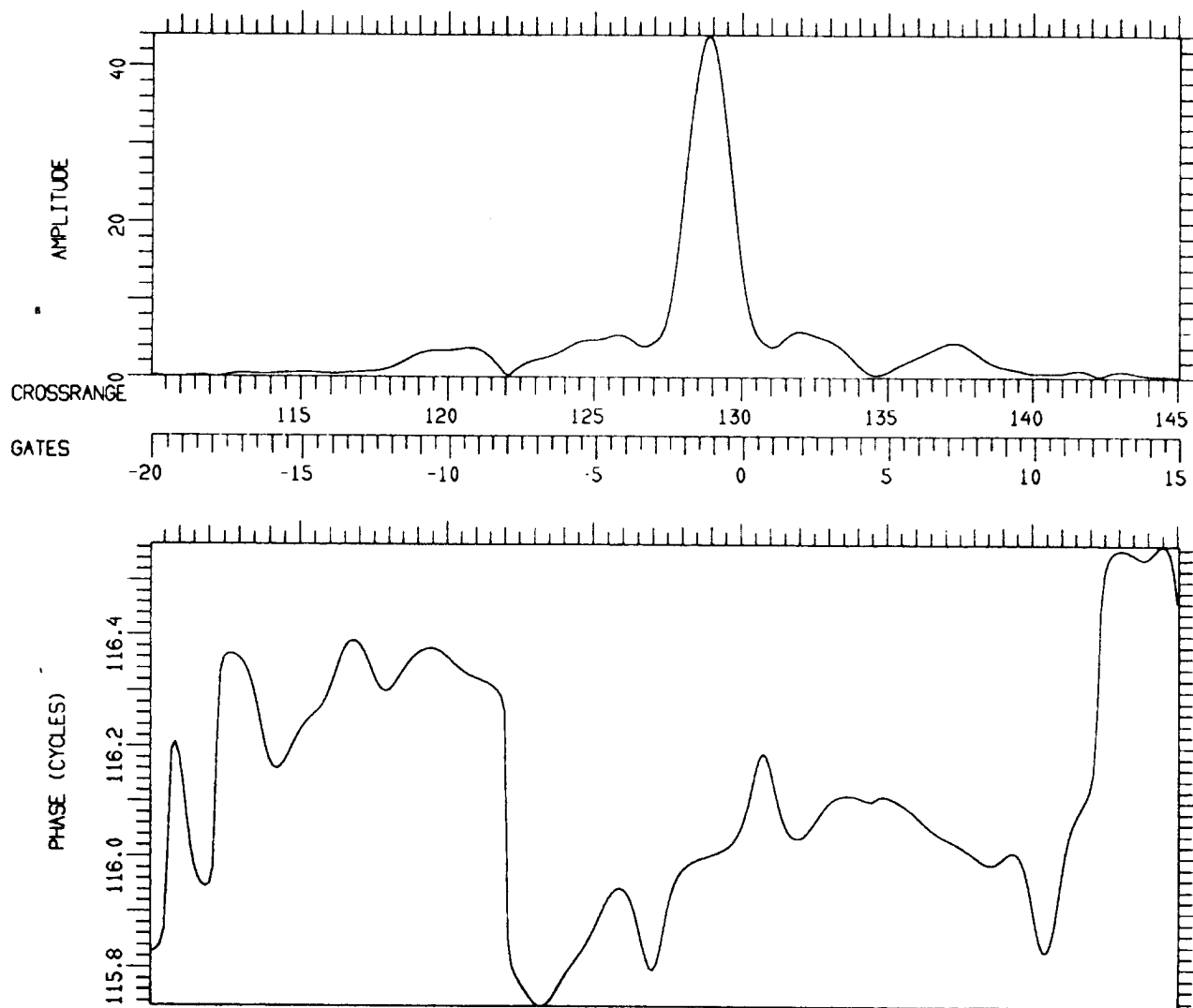


Figure 4.7. Transform After Motion Compensation.

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1. THE VARIETY OF CONDITIONS FOR GROUND VEHICLE IDENTIFICATION

Ground vehicles have different sizes, they can have rather different weights, and can be constructed rigidly or with light sheet metal. They can have rather different suspensions, and they may be moving on good roads, poor roads, or off the road. Their speed can range from very slow to fast. All these various conditions affect imaging and vehicle identification. In this introductory section we discuss the consequences of the variety of conditions, so that the examples discussed in this report can be placed in proper perspective.

1.1 CONSEQUENCES OF VEHICLE HEIGHT

If the height of a ground vehicle is small, for imaging purposes its motion may be considered two-dimensional. Suppose that the depression angle of the radar beam is very small. The Doppler that permits resolution of the vehicle features located in the same range gate then is caused by the apparent vehicle rotation in the ground plane. The vehicle may also have a back-and-forth yaw motion. If the angular change caused by the yaw motion is large enough to permit a usable degree of crossrange resolution, the yaw motion itself can be utilized for imaging. If the yaw motion is too small for this purpose, it must be measured and taken out from the data by resampling. The vehicle may also roll or pitch. However, as long as the vehicle height is small enough, these motions will have little consequence.

For tall vehicles, on the other hand, roll motion may introduce a significant roll Doppler that must be taken into account in imaging and image analysis. If the radar can observe at least one full roll cycle, we can circumvent any problems introduced by the roll Doppler by working with the average roll Doppler. This is not so, however, if only a fraction of a roll cycle can be observed. The roll motion will translate the responses of the high features in crossrange, so that their crossrange positions will be falsified. We then can use only the range positions of these features in the target identification process, utilizing crossrange resolution only for the improvement of range resolution and range accuracy. The same conditions exist for reasonable yet relatively small depression angles of the radar

beam. As the depression angle is increased, the consequences of yaw and roll will change with the changing geometry, with obvious modifications of our reasoning.

1.2 MOVEMENT ON ROADS AND OFF ROADS, SLOW AND FAST

If a vehicle is moving slowly on a road, the bouncing, yawing, pitching, and rolling motions will be small, so the vehicle image will not be severely smeared in crossrange. This is important both for vehicle detection and identification. A vehicle image with little smearing in crossrange implies that the signal-to-noise and signal-to-clutter ratios are not significantly lower than for stationary vehicles. However, the detection of the moving vehicle might still be more difficult if the translational motion of the vehicle superposes its image on terrain with a high clutter level. For example, the vehicle image could appear on top of a tree. Even when DPCA processing is used for clutter suppression, the signal-to-clutter ratio might be lower than desirable.

If the vehicle is moving with considerable speed on the road, the bounce/yaw/pitch/roll motion may be larger than when the vehicle is moving slowly, and these motions will generally have shorter periods. The consequence will be an increase in the crossrange interval over which the image is smeared, causing more severe signal-to-clutter problems than with slowly moving vehicles. This will make detection and identification more difficult. In addition to the clutter problems, we now have the modulation effects introduced by the various motion components of the vehicle. The same remarks apply as in Section 1.1.

The worst imaging conditions occur when a vehicle is moving off the road. Even though the speed of the vehicle will generally be lower than when it is moving on a road, the unevenness of the terrain greatly magnifies the bounce, yaw, pitch, and roll components of the motion. The consequence is a smearing of the responses of scatterers over a large number of crossrange gates, so that it becomes difficult or even impossible to find a range gate with a scatterer sufficiently dominant to allow the ready derivation of the phase function introduced by the motion of the scatterer. This situation poses the most difficult problem of motion compensation.

1.3 RIGID VERSUS FLEXIBLE VEHICLES

The preceding discussions assume that the vehicle is so rigid that yaw and roll motions do not deform the body of the vehicle even by the small amounts that would affect the radar measurements. For vehicles that can bend and flex, on the other hand, there is an additional problem in that different parts of the vehicle may move differently. The vehicle motion then no longer can be described by yaw, pitch, and roll, which components assume a rigid vehicle body. Depending on the situation, we can sometimes eliminate the consequences of the flexing components if we can observe the vehicle over at least one flexing cycle. This may still be possible to some degree even when the observation period is somewhat shorter, provided we can determine the instant at which the flexing motion temporarily goes through a zero.

1.4 MOTION ALONG A STRAIGHT PATH VERSUS TURNING MOTION

If a vehicle is moving along a straight path, the conditions are little changed from those for a stationary vehicle as long as the bouncing, rolling, pitching, yawing, and flexing motions are negligible. If the motion components are larger, they will introduce the problems mentioned above, but the basic resolution conditions will still be those of a stationary vehicle. The situation is rather different if the vehicle is turning.

Normally, a SAR surveillance radar is designed to produce images with specified resolution performance in range and crossrange. Suppose that resolution in both dimensions is relatively high; say, it is one foot. If the vehicle is turning, the aspect angle change during the time interval needed for achieving 1 ft crossrange resolution on a stationary vehicle will be quite large. In principle, we could use this aspect angle change to achieve a crossrange resolution much finer than 1 ft. However, such a high crossrange resolution is difficult to achieve and may even be meaningless for a vehicle that cannot be modeled by a set of point scatterers in fixed positions (as is typical in practice). It appears much more practical to utilize the excess dwell time for analyzing the vehicle motion, and choosing the best time or times for imaging to avoid distortions caused by the various vehicle motion components.

1.5 ASPECT ANGLE

Detecting and identifying a moving ground vehicle is made much more difficult by the presence of ground clutter. Whereas for stationary ground vehicles the motion compensation is that for the entire SAR scene, for moving ground vehicles we must perform a separate motion compensation for each vehicle. This is difficult to do in the presence of ground clutter, and the degree of difficulty increases with the smearing of the SAR image of the vehicle due to its various motion components. The problem becomes particularly severe if the smeared image is shifted in crossrange by an amount that happens to superpose it on an area of strong clutter. Thus it is highly desirable, and in many cases mandatory, to use clutter suppression based on the vehicle motion, such as the DPCA method.

As with all moving-target clutter suppression methods, DPCA processing depends on the target having a range rate relative to that of the clutter. This relative range rate disappears when the target is viewed at broadside, so that clutter suppression causes a suppression of the target as the broadside view is approached. The resulting difficulties combine with the general problems of the motion compensation and target identification near broadside. Thus, the question with DPCA clutter suppression is how close to broadside can we still detect and identify the vehicle? Near broadside the conditions are similar to those for stationary targets, except for the smearing of the image due to bouncing, yawing, pitching, rolling, and flexing motions. In the aspect interval in which DPCA suppresses the target return we thus must use the data before clutter suppression. There is at least the possibility that a moving vehicle can be detected and identified, because near broadside the range rate is so small that the vehicle image cannot be shifted much in crossrange. Rather than the image being superposed on high-clutter terrain, the vehicle will tend to mask the clutter underneath it.

2. MOTION COMPENSATION FOR TARGETS WITH FLEXING/THREE-DIMENSIONAL MOTION

2.1 FOCUSED IMAGE VERSUS SCATTERER-COMPENSATED IMAGE

It is almost universal radar parlance to speak of the focusing of radar images, and of the goal of the motion compensation being to generate a focused image. This is not just inappropriate. It betrays a lack of insight into the problems of target identification by radar. This type of thinking also tends to misdirect the efforts aimed at solving modern radar problems.

For a justification of these statements, we start by considering a photograph so poorly focused that we cannot recognize the object in the photograph. As we progressively increase the quality of the focusing, the shape and detailed features of the object will become clear, so we can recognize it. When photography is used as the basis for target identification, we must focus the image sufficiently well. The obvious requirement on the degree of focusing is that the target features be recognizable in the photograph.

The situation is quite different for radar imagery. Since the radar wavelengths are much longer than wavelengths at visible light, the backscattering at radar wavelengths is drastically different from that at visible light. Also, the combination of range and Doppler resolution is not equivalent to azimuth and elevation resolution in optics. No matter how well the image might be focused, most targets cannot be readily identified from their radar images, in particular not if this is to be done automatically. Identification on the basis of the target shape, in analogy to the optical approach, has been tried (at great expense) for the past 30 years, but without success. We need different methods for target identification. Specifically, we must be able to extract from the image information on the important target features, in particular the positions of these features on the target. This requires that the individual feature responses be well focused.

Even this modified statement, going from the focusing of an image to the focusing of individual responses, is inappropriate. The term focusing clearly refers to the intensity image. A focused response would be a sharp response in the intensity image. What about the phase function of the response? To exploit the inherent resolution performance of radar, we must analyze the complex responses of the image, which includes the phase functions

of the individual responses. Specifically, the phase function of a response from a point scatterer must be linear. This is not a matter of focusing, but of compensating the responses of the scatterers. The term focusing of a response ignores the requirements on the phase function entirely. Thus we should speak neither of the focusing of an image nor of the focusing of the responses of an image.

The appropriate view is that the goal of the motion compensation is to generate an image with well compensated responses. We can also express this fact by stating that the goal of the motion compensation is to generate a scatterer-compensated image. Only in that case, which permits utilization of the phase functions of the responses, can we achieve the limiting radar resolution of $1/B$ in delay and $1/T$ in Doppler, with B the signal bandwidth and T the coherent processing time.

In the simplest case where a SAR image is generated of a stationary ground vehicle, the goals of focusing the image and of generating a scatterer-focused image are the same. Provided the motion compensation is satisfactory, a focused image also implies that a point scatterer on the target has the sharpest possible response and that the phase function of the response is linear. With an unsatisfactory general motion compensation, we must improve the focused image into a scatterer-compensated image, using corrections of the same kind as needed for ISAR imaging of a rigid moving vehicle. With moving ground vehicles (or aircraft) we should not even think in terms of focusing, because it is meaningless.

The following discussion will make this point even stronger. Suppose a moving ground vehicle is totally rigid and has no bouncing motions, as if it were rotating on a turntable. In that case, but only in such a special case, can we develop a motion compensation that will work over the entire vehicle. This becomes more difficult, and probably impractical, when the vehicle bounces, yaws, pitches, and rolls. Nevertheless, in principle it is conceivable to develop a motion compensation that takes the different motion behaviors of the parts of the vehicle into account, as long as the vehicle may be considered rigid. However, this is rarely the case when the motion of a vehicle is complicated. Bending and flexing effects then become important, so that the different parts of the vehicle must be individually compensated. Focusing of the image is an inappropriate term.

When a vehicle has the type of complicated motion behavior that leads to significant consequences from flexing and bending, another problem may arise. As long as we can measure a full cycle of the bending/flexing motion, we can image at a time at which the consequences are small, or we can measure the motion cycle and compensate its effects. Then it is possible to generate a scatterer-compensated image in which the responses of point scatterers are at their correct crossrange positions. When one cannot evaluate the entire motion cycle, or when the observation time is too short, one can still compensate the responses so point scatterers have sharp responses with linear phase functions, but the responses may be shifted in crossrange. Thus we must distinguish between scatterer-compensated images with true crossrange and those without true crossrange.

In the case where the crossrange positions of scatterers are falsified, it is even less justified to speak of image focusing. Aside from such a misleading terminology, it might appear that imaging with high crossrange resolution then is of no use, so that we should try to identify the vehicles on the basis of their range profiles. The first part of the statement is incorrect even though the second part is correct. Even should the crossrange positions of the scatterers be so greatly falsified through bending/flexing effects that they become useless, which will not often be the case, crossrange resolution is still needed. By resolving the scatterers in a range gate in crossrange, regardless of how much falsified the crossrange positions might be, we still can perform accurate range measurements. If we had only range resolution, the accuracy of the scatterer positions in range would be destroyed by the lack of crossrange resolution and the resulting mutual interference between the scatterers.

The point to be made is that work that is directed toward generating a radar image that appears well focused is totally irrelevant to the problem of radar target identification. Before one can judge the success of generating a usable image, one must have in mind a way of identifying the target. The requirement on the image then becomes that the image allow target identification. Work that addresses the focusing of the image without continuing toward target identification is meaningless. We are not interested in vehicle images. We are interested in vehicle identification. We must judge the success of generating an image only by attempting to identify the target.

As will be discussed further below, the difference between focusing an image and generating an image with usable responses is huge when the target is moving.

2.2 THE MOTION COMPENSATION PROBLEM

Doppler processing requires that a target (or, in the case of radar imaging, each scatterer on a highly resolved target) move with constant Doppler. Hence, when a usable range/Doppler image of a target is to be generated, one must preprocess the data in such a way that each scatterer appears to be moving with constant Doppler. This preprocessing step is referred to as the motion compensation. The motion compensation is relatively easy when three requirements are met: The target is moving very steadily, the motion is essentially in a plane, and the target is rigid. The motion compensation becomes more difficult when the requirement that the target motion be smooth is not met. An appropriate motion compensation for this case is described in [1]. In this section we treat the extension of the motion compensation needed when the other two requirements are not met, so that scatterers in different locations on a target move differently.

It has been customary to treat radar imaging more or less like optical imaging, setting as an objective the generation of some kind of "focused" image. However, even in the simplest case where a rigid body is moving in a plane, the approach leads to what appear to be unsolvable problems of target identification. The backscattering at radar wavelengths just is too different from that at optical wavelengths. The difficulties multiply if the motion of the target cannot be assumed to be two-dimensional and if the target is not sufficiently rigid. For all of the following we assume the necessity of generating an image in which the individual responses can be associated with specific scatterers on the target. We show that the objectives of the motion compensation are achievable even under relatively difficult circumstances, at least if one makes use of the Complex-Image Analysis methods [1].

2.3 PRINCIPLES OF MOTION COMPENSATION AND IMAGING

In the simplest case where a rigid target is turning in a plane, the objective of the motion compensation is to keep each scatterer on the target in its range cell, and to transform the motion of every scatterer into one of

constant Doppler. Doppler processing of all range gates on the target then leads to a range/Doppler image of the target. As long as one attempts only to generate an image that appears well focused, there is no limit on the ingenuity with which motion compensation methods can be developed.

The situation is quite different when the objective is to generate undistorted image responses that allow the accurate measurement of scatterer positions and the analysis of the characteristics of special features. In this case we must not use any method for estimating the range and Doppler motions of the target that can introduce fluctuating Doppler residuals. If we measure a variable Doppler and fit a flexible spline function for compensation purposes, the spline will sometimes be a little above the measured phase curve and sometimes a little below. It takes very small phase deviations to generate significant crossrange sidelobes that can be mistaken for scatterer responses or might mask such responses. Once these fluctuating phase residuals are introduced into the data, they cannot in practice be removed by any subsequent compensation steps.

We need a different approach. For the first motion compensation steps we cannot avoid using estimates of the behavior of the entire target, such as tracking the range centroid of the target (or correlating consecutive range profiles) and tracking the Doppler centroid of the target. However, the fits to these motion estimates must be of low order, preferably linear or at most quadratic. This prevents the introduction of fluctuating phase residuals. After these crude compensation steps, we must switch to the compensation of individual scatterers rather than the target as a whole. This largely avoids the problems of fitting to variable Dopplers because the largest source of these variations comes from the interference between the scatterers in the same Doppler cells. Equally important, performing a compensation on a scatterer response allows one to check the quality of the compensation. If the quality is insufficient, we select another scatterer for the next compensation step. If we cannot find a scatterer for which a satisfactory motion compensation can be performed, we must reduce the imaging time. It is much better to implement less crossrange resolution than to have an image with high nominal crossrange resolutions in which the scatterer positions cannot be measured with acceptable accuracy.

A motion compensation of this type is described in [1], but under the assumption that three-dimensional motion effects are insignificant or can be accommodated as corrections. This is a good assumption for aircraft that are not heavily maneuvering, because the fuselage of an aircraft is not very high. The problems from three-dimensional motion become more significant for tall vehicles, such as the one treated in this chapter. For a tall vehicle even a slight roll motion can cause a significant displacement of the responses in crossrange. Moreover, these shifts vary for the scatterers on the vehicle, depending on their locations. The problems are further magnified if the vehicle is flexing, since the motion introduced by flexing will vary over the vehicle. On the assumption that we want to generate an image in which individual scatterer responses can be analyzed, we need an extended motion compensation.

We stated above that an apparent focusing of an image is not adequate because we want to focus the individual responses. As long as the motion is essentially two-dimensional and flexing effects are insignificant, we can generate an image in which all responses are focused [1]. This is so because responses close to each other in the image will come from scatterers close to each other on the target. This need not be the case for three-dimensional motion and flexing, so that we cannot process the entire image in a manner that will focus the responses everywhere in the image. Instead, we can only focus the responses individually. This is perfectly adequate, however, because we are interested in the individual responses rather than the image. The objective of the motion compensation then becomes the focusing of the N strongest responses, which are to be used for target identification.

With this understanding, the objective of our motion compensation is threefold: First, each feature response should be fully compressed in crossrange, so that interference among responses from scatterers in different crossrange positions is minimized. The range positions of the features, which are extremely important for target identification, then can be measured with high accuracy. Second, the responses should be compressed in crossrange so that closely separated responses can be resolved. Then we can measure the positions, and sometimes the characteristics, of individual features in the same range gate but with different crossrange positions. Third, for those cases where at least a full cycle of the variable motion component of the

target can be measured, we need well compressed responses in order to achieve a high accuracy in the crossrange measurement.

2.4 VEHICLE IMAGE AFTER A FIRST-STAGE MOTION COMPENSATION

For our demonstration we will use radar data with 1 ft range resolution on a Winnebago RV that is turning (presumably smoothly) on a paved surface. The motion behavior thus should be expected to be fairly benign, without strong bouncing, yawing, pitching, and rolling motions. However, because of the size and construction of such a vehicle we find significant effects that can be attributed to flexing and the large height of the vehicle, the latter introducing a degree of three-dimensional motion. The wavelength of the radar is only 2 cm, so that the imaging is susceptible to very small motion effects. We are using the data after clutter cancellation via DPCA processing [2], even though in this particular instance clutter cancellation may not be important.

The motion compensation described in [1] is a multi-step compensation that leads to a progressive improvement of the image quality. It starts with range centroid tracking of the entire target, followed by Doppler centroid tracking of the target, and for the following compensation steps switches to the tracking of individual scatterers. When the assumptions of rigidity and two-dimensional motion are violated, the compensation steps involving individual scatterers must be modified. Thus we start here with the image after range centroid and Doppler centroid tracking. This image is shown in Figure 2.1. It is a peaks plot image, in which the locations of maxima in the intensity image are indicated by dots whose diameters are proportional to the amplitudes of the maxima. The background below a level of -30.5 dB relative to the highest peak of the image is not shown. There is no way to determine the correct crossrange scale from a single image, so that the crossrange scale is arbitrary. The image thus appears distorted. As pointed out above, the objective is not to generate a well-compensated image, but to compensate those image responses to be used for target identification, which generally means the stronger responses.

2.5 MOTION COMPENSATION OF AN IMAGE RESPONSE

Briefly summarizing the principles [1], in order to motion compensate a response, we must measure its motion component with nonconstant Doppler. This

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CLIP HIGH = 0.500

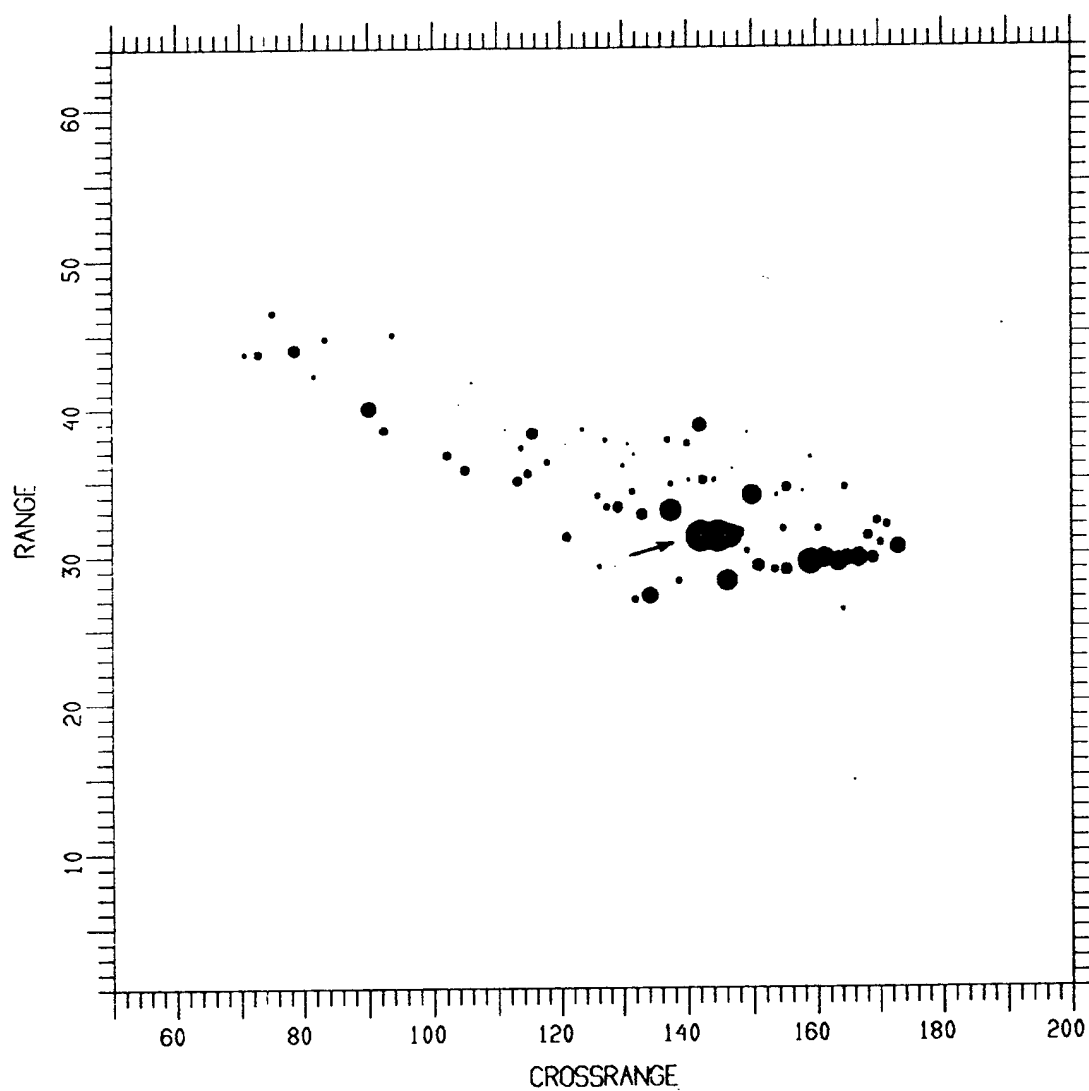


Figure 2.1. Vehicle Image After Range and Doppler Centroid Tracking.

is done by taking a fixed-range cut through the (complex) response, taking the Fourier transform of the response, and measuring the phase function of the transform. Since phase is proportional to range, the phase function describes the range wander of the scatterer. The transform window must not be too small, because cutting off the high response frequencies by use of too narrow a window will smooth the variations of the phase function.

The practical problem of measuring the phase function is that the motion compensation residual from the first two motion compensation steps typically leaves the responses smeared. Choosing the required wide transform window will usually lead to the inclusion of parts from other smeared responses, causing a gross distortion of the phase function. This is the central problem of the motion compensation. The only apparent practical solution to this problem is to start with the very best response that can be found in the image, and then slowly modify the compensation as one proceeds from one response to the next.

We now apply these principles. Attempting to measure the phase functions of the stronger responses, we find that the response best suitable for our purpose is the one marked by an arrow in Figure 2.1. The image cut in the range gate of this response is shown in Figure 2.2, with the amplitude function on top and the phase function at the bottom. Including the important tails, the response is spread over about 10 crossrange gates, which is a modest degree of smearing and due to the fact that the vehicle is turning rather smoothly. We want to compress the response so that its width is nearly that of a response from a point scatterer, and do this without the introduction of unacceptably high crossrange sidelobes. The crucial point is that there is no high interference close to the response, so that the transform window can include half of the high frequencies of the response without including parts of interfering responses.

The transform over a window from Gate 125 to Gate 165 is shown in Figure 2.3. Since the percentage amplitude modulation is small, the phase variations introduced by the interference are also small, and hence we obtain a good fit to the phase function, as indicated in Figure 2.3. The quality of the fit is determined by the values of the deviations between measured and fitted curve, which determine the level of the crossrange sidelobes. The fit is good because the maximum deviations are much less than 0.1 cycles. When

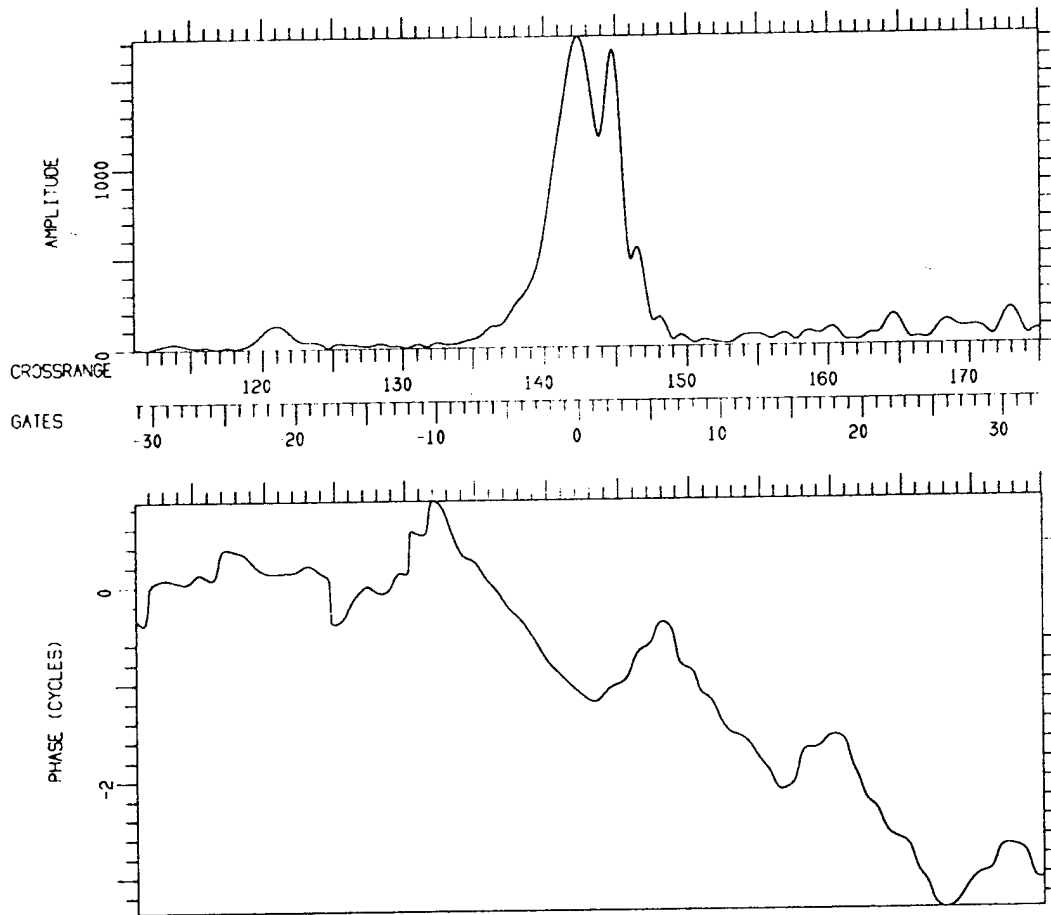


Figure 2.2. Image Cut in Range Gate 31.2.

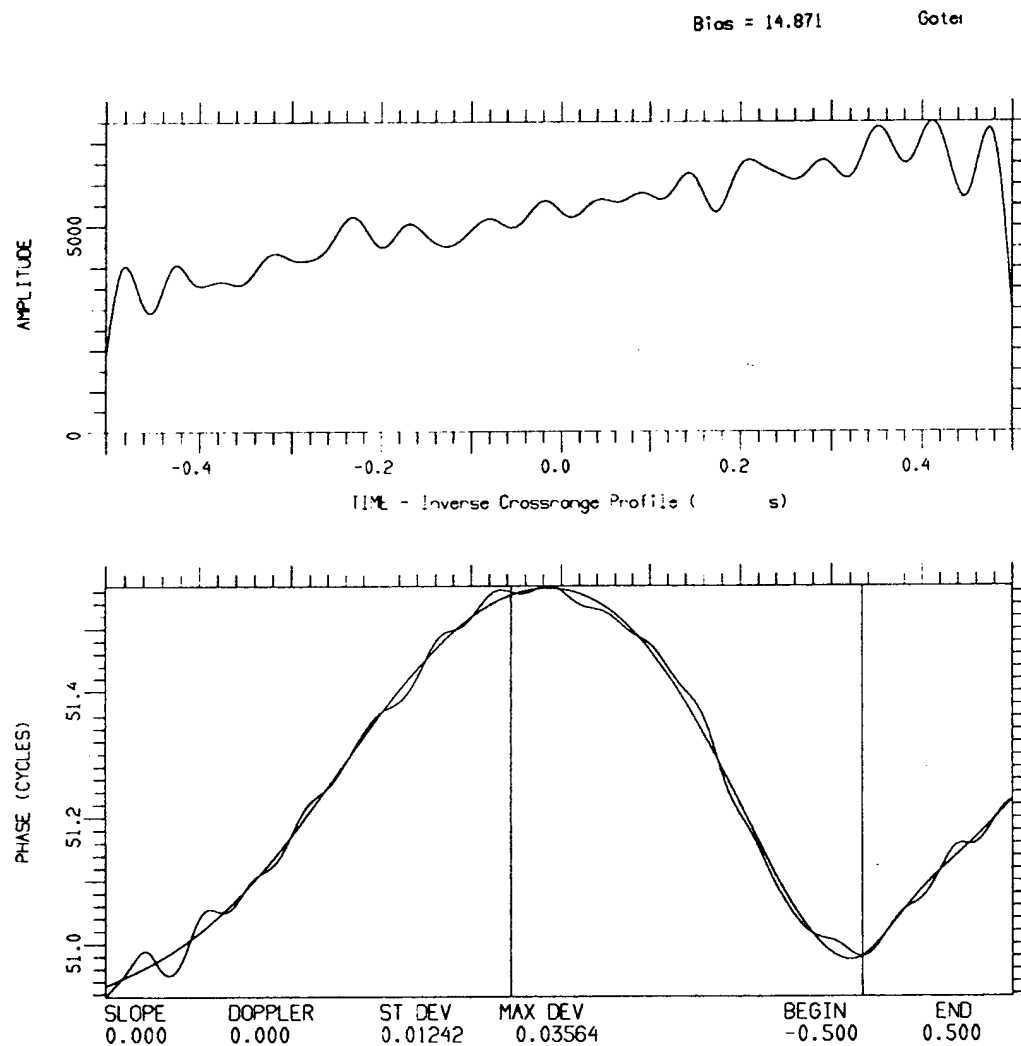


Figure 2.3. Transform of the Response of Figure 2.2.

the fitted phase function is used to compensate the range gate of the response, we obtain Figure 2.4. The printout on the right margin shows that the half-power width relative to that for a point scatterer is 1.015, which is excellent, and that there are no high crossrange sidelobes. Thus we have properly compensated the strongest response in the image. Note that one must remove the linear trend in the phase function before fitting a spline, since otherwise the crossrange position of the response would be changed.

2.6 COMPENSATION OF OTHER RESPONSES

In the case of a rigid body with smooth two-dimensional motion one could find many isolated responses, so that the phase compensation could be carried out despite the fact that the responses are smeared. If the motion is not very smooth, this becomes difficult, and we must be satisfied if it is possible to find two suitable responses from which the target motion can be derived. In the case considered here, it is difficult to find good responses in the sense explained, and yet we would like to compensate individual responses. Evidently, if we cannot compensate a sufficient number of responses, identification of the target will not be possible. We will subsequently demonstrate the difficulties of response compensation and the ways to solve these difficulties.

Consider the response adjacent to the one marked in Figure 2.1, positioned in Range Gate 33. The image cut in the range gate of the response is shown in Figure 2.5. However we try to place a transform window, the transform is not suitable for our purposes. With the best window as marked in Figure 2.5 we obtain the transform of Figure 2.6. The rapid phase changes are so large that no phase trend can be measured. We cannot compress the response. The way to solve the problem is to attempt to find a simpler response in the vicinity and perform a compensation, and use the same compensation on the response of Figure 2.5.

If the compensation does not work well enough, it might be good enough for deriving an added compensation for the partly compressed response. If this also does not work, not just for one or the other response but for most responses to be utilized, then we are attempting to achieve a crossrange resolution too high for the behavior of the target. We must reduce the imaging time and try again. Of course, we will reduce the imaging time by

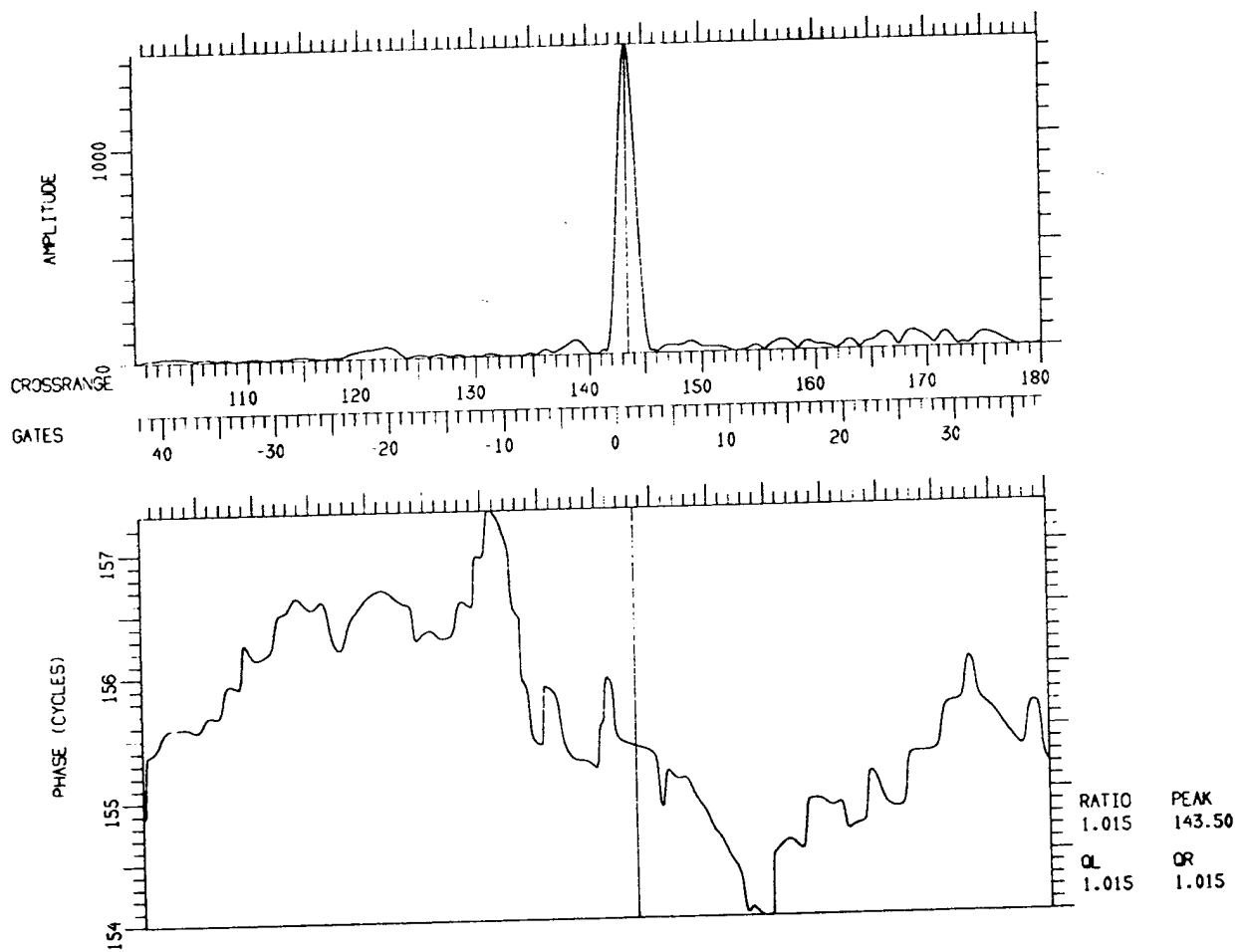


Figure 2.4. Response After Motion Compensation.

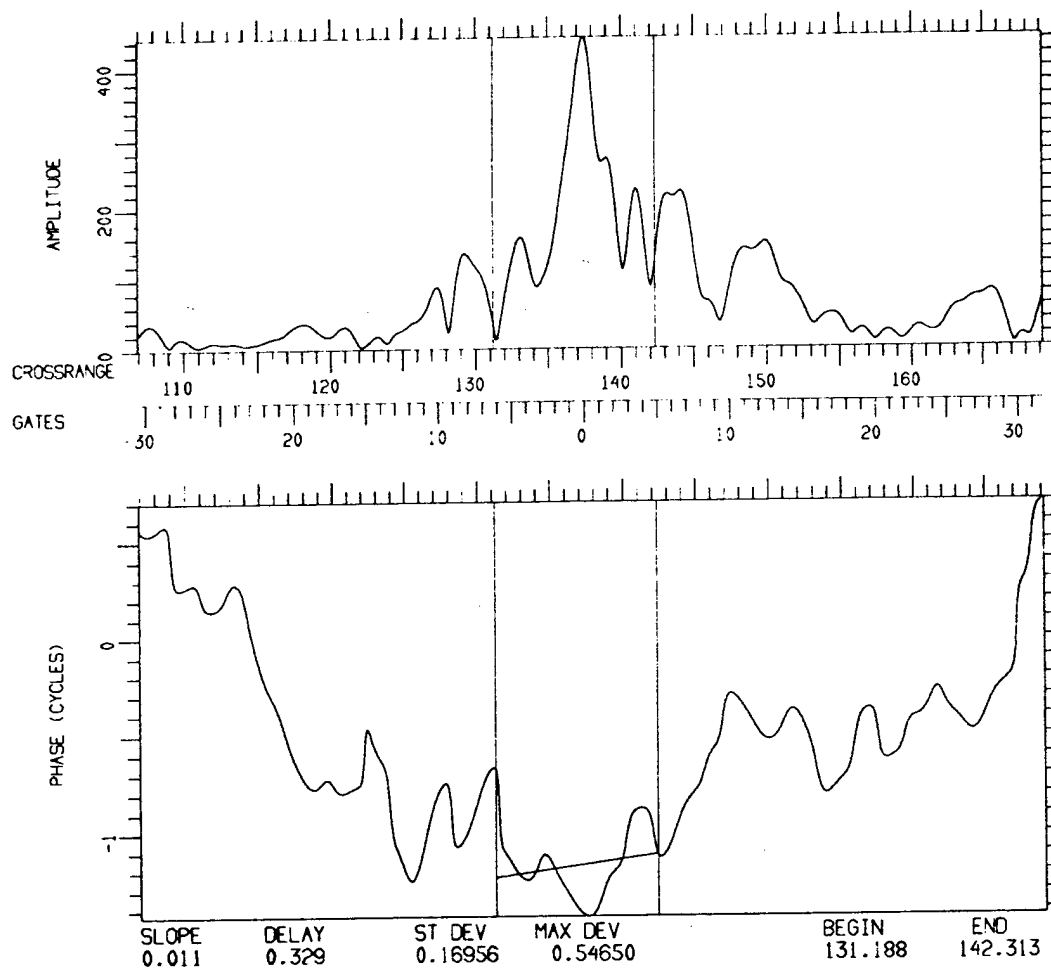


Figure 2.5. Image Cut in Range Gate 32.9.

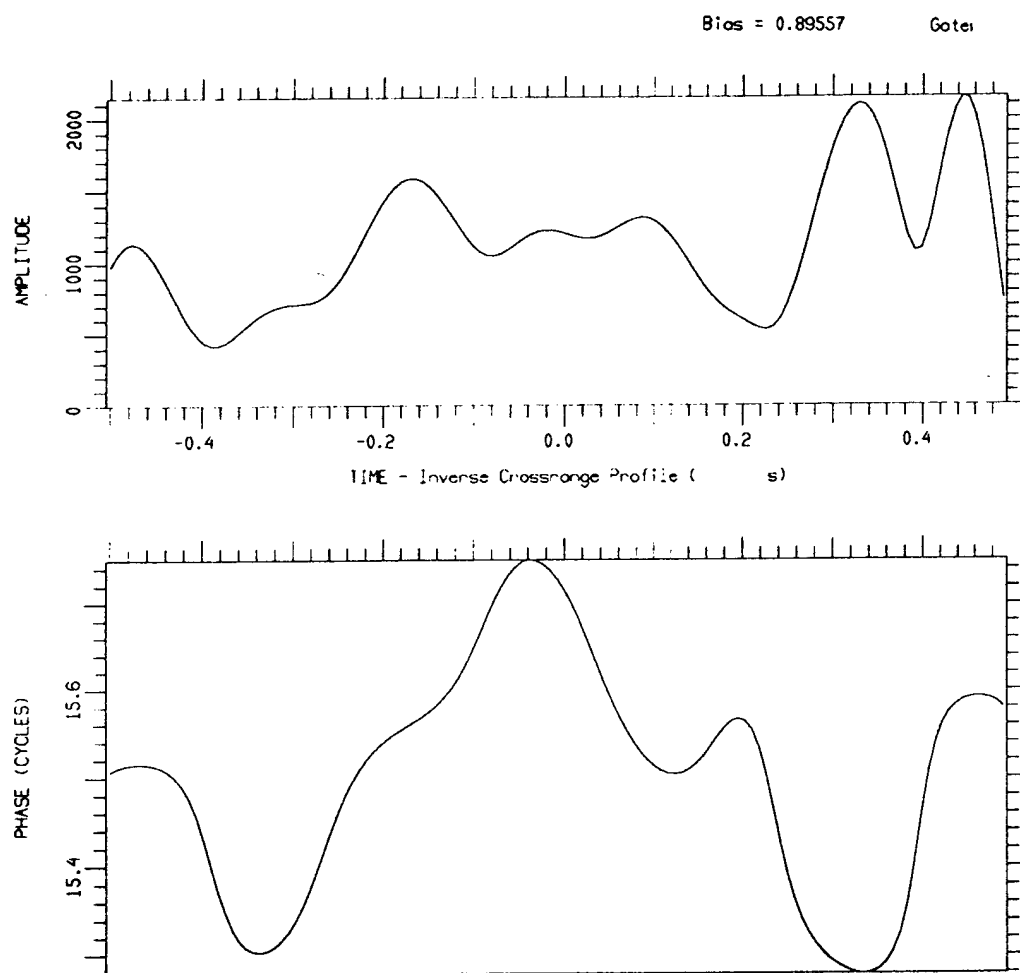


Figure 2.6. Transform Over the Window Marked in Figure 2.5.

selecting the time interval over which the responses show the best behavior after the crude compensation steps, with the behavior again judged in terms of the properties of their phase functions.

We select the next major response, in Range Gate 34 and Crossrange Gate 150, for which the image cut is shown in Figure 2.7. Since we must not extend the transform window into the strong responses to the left of the response of interest, we place the window as shown in Figure 2.7. We obtain the transform of Figure 2.8. Taking note of the scale of the phase function, we conclude that the only unacceptably large phase jumps are those associated with the three deepest amplitude minima. We must remove these phase jumps in order to allow fitting a spline function, but must do this without too large an error. If we remove too much or too little of the phase jumps, we introduce a slowly varying bias into the phase function, which in turn will result in crossrange sidelobes.

The phase function after phase jump removal and the spline fit are shown in Figure 2.9. After applying the corresponding phase compensation, the image cut of Figure 2.7 changes to that of Figure 2.10. Note the sidelobe immediately to the right of the main response. This is the consequence of errors in the estimate of the magnitude of the phase jump. In this case the sidelobe is still acceptable, but if it were higher we would have to change the phase jump estimates until the sidelobes have an acceptable magnitude. In practice this process must be fully automated. For our purposes here we consider the result satisfactory. When the same phase compensation is applied to the image cut depicted in Figure 2.5, for which no compensation was possible earlier, we obtain Figure 2.11. We now have a well compressed response, so that no iterative compression step is needed.

2.7 COMPENSATION OF SETS OF SCATTERERS

The reason that we were able to take the transform of a smeared response and derive a phase function usable for compensation is that a single scatterer dominated over a sufficiently wide crossrange interval (more than ten gates). If comparable scatterers are closely spaced, one must unscramble the phase components due to the motion compensation residual and due to the interference between the scatterers. This may not be possible in all cases.

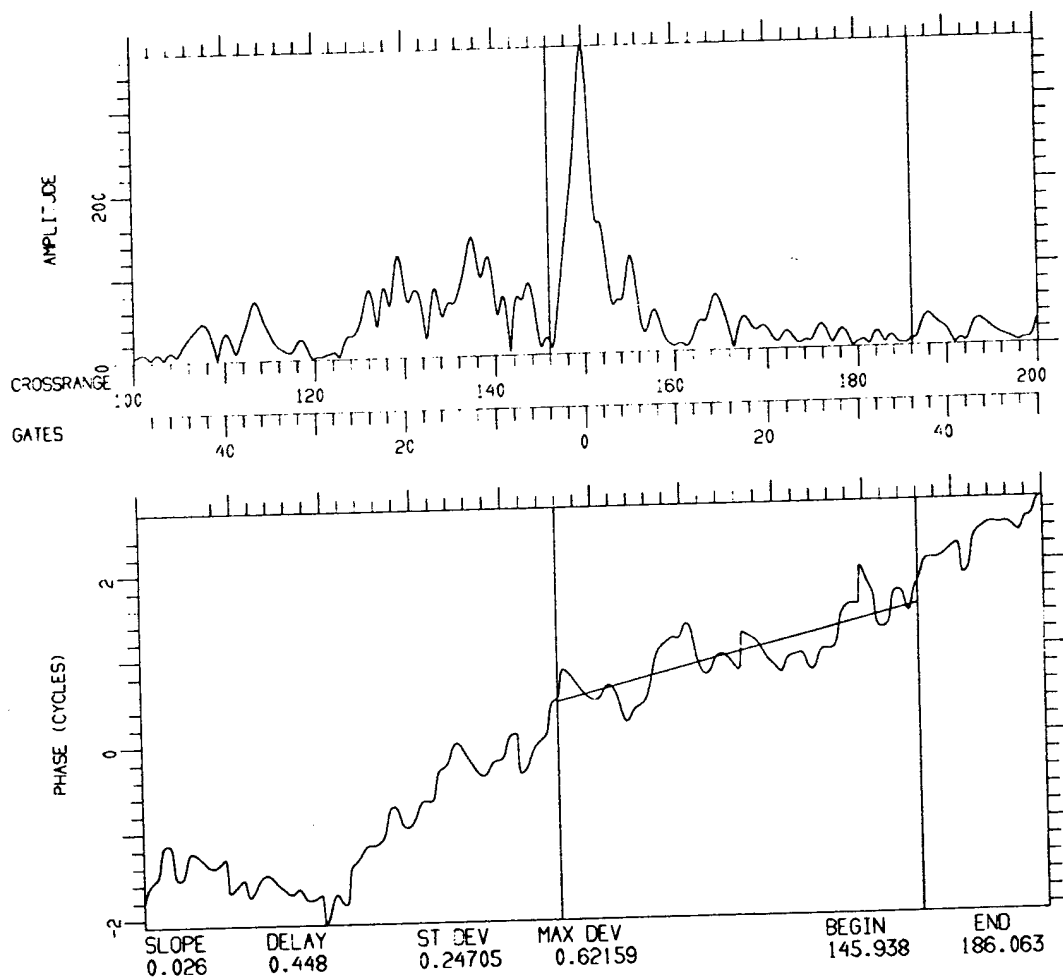


Figure 2.7. Image Cut in Range Gate 34.

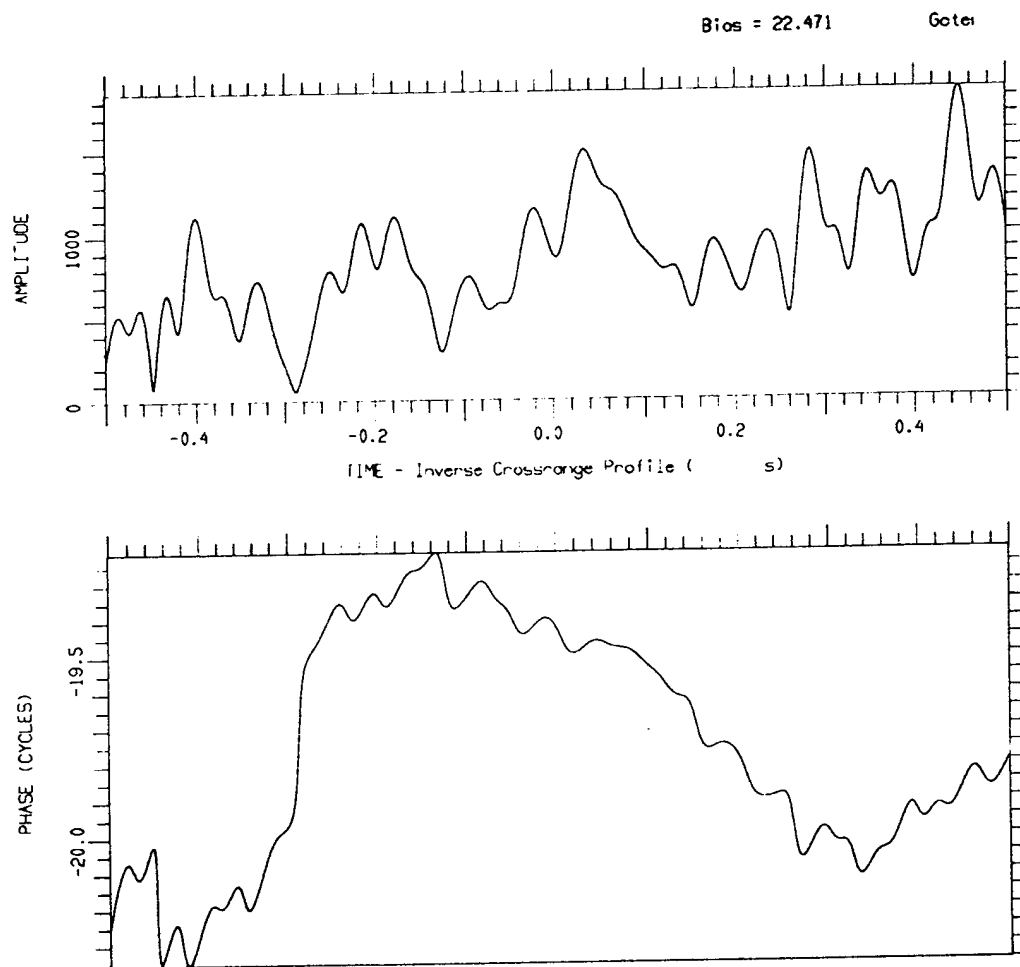


Figure 2.8. Transform Over the Window Marked in Figure 2.7.

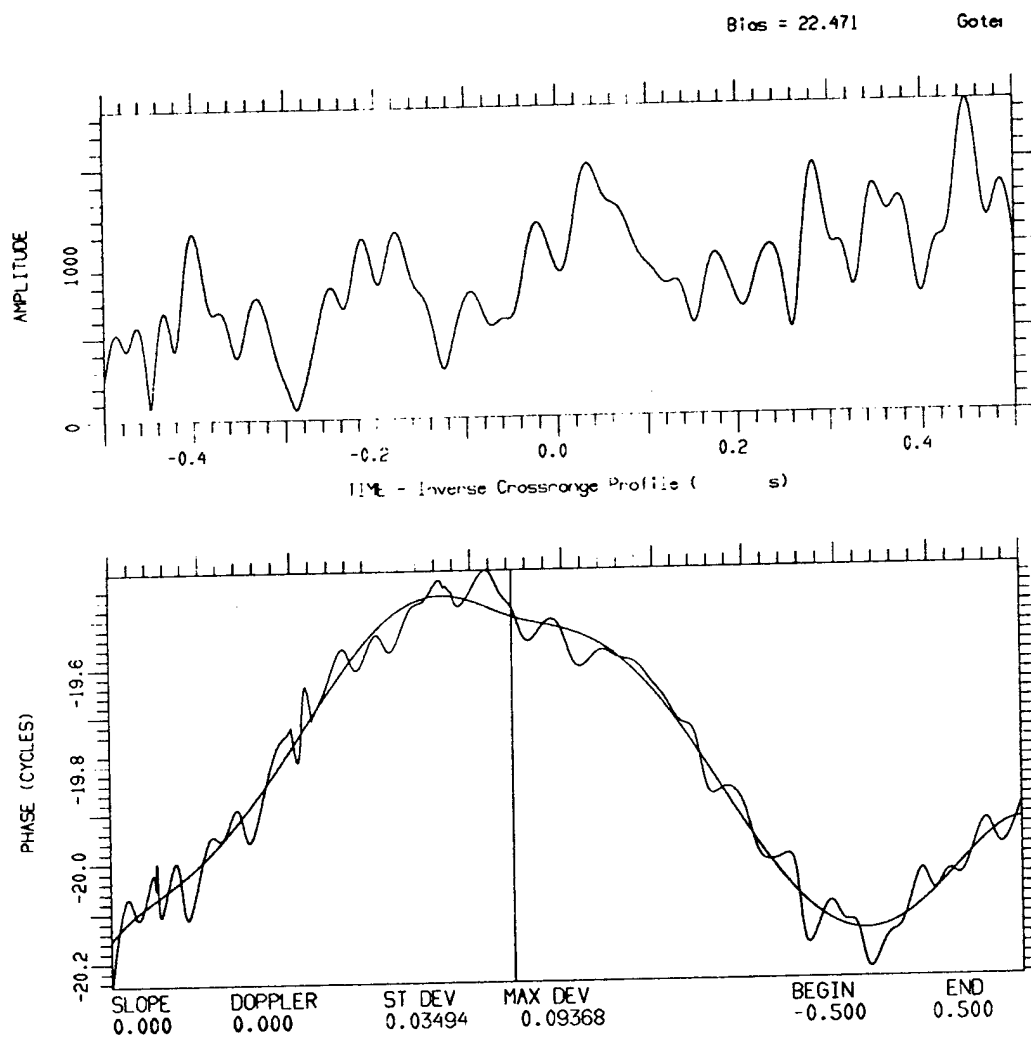


Figure 2.9. Spline Fit for the Compensation.

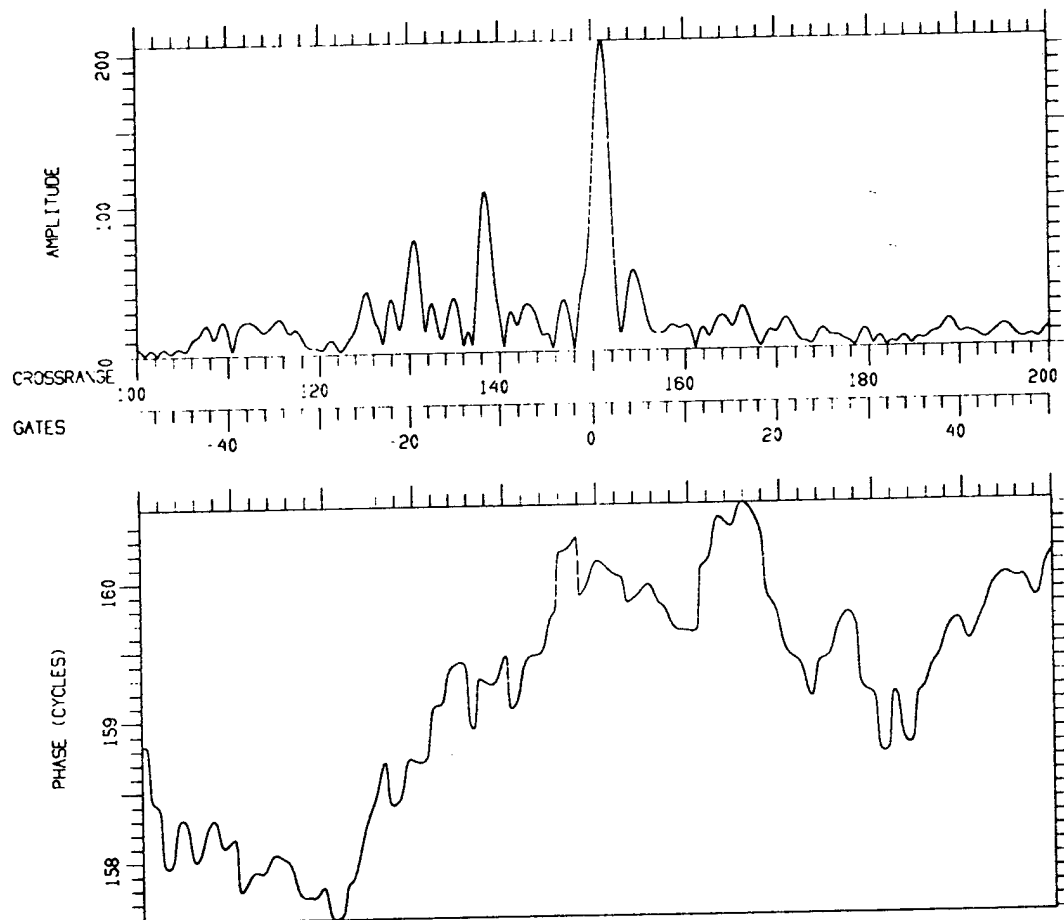


Figure 2.10. Image Cut in Range Gate 34 After Compensation.

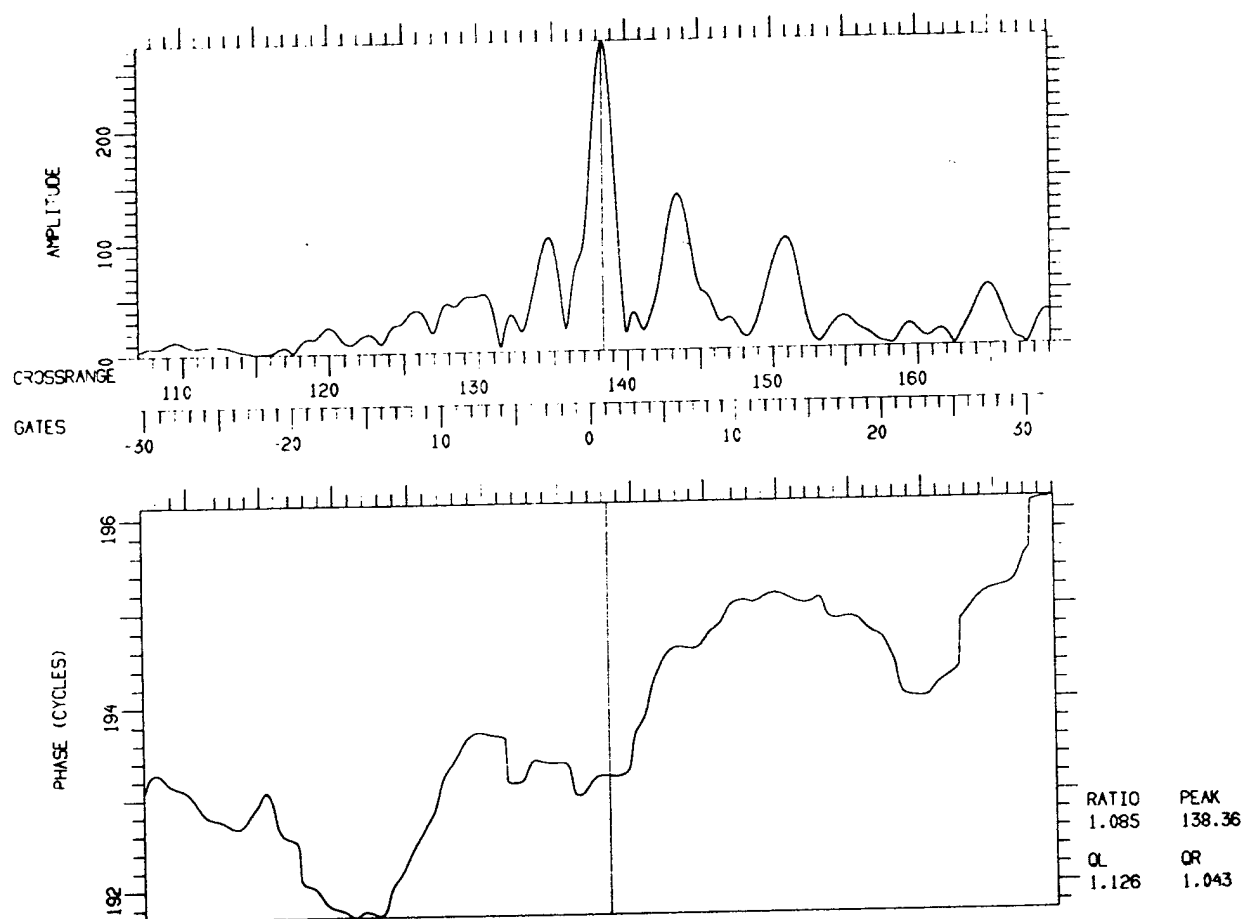


Figure 2.11. Image Cut in Range Gate 32.9 After Compensation.

If we do not know a way of unscrambling a complicated phase pattern, we must use the motion compensation from a nearby single scatterer.

As an illustration, in Figure 2.12 we show the image cut in Range Gate 36.4, which in accordance with Figure 2.1 contains important scatterers. In Figure 2.12 the corresponding responses are centered in about Gate 103. The transform obtained from these responses is totally unusable for deriving a phase compensation, and so we do not show it. Instead, we obtain the phase function for the response centered in Range Gate 40.1 and Crossrange Gate 90.3, as shown in Figure 2.13. Note that the phase function, and hence the scatterer motion, is rather different from those investigated earlier. After removing the larger phase jumps associated with the deep amplitude minima, fitting a spline function, and compensating the range gate depicted in Figure 2.12 we obtain Figure 2.14. The marked peak still has a rather larger relative half-power width. The reason may be that the motion compensation still is not adequate, or that it is good but the response is a composite from two scatterers.

The decision between the two cases can be and must be made by testing the properties of the response. If the large width of the response is due to an inadequate motion compensation, a refinement is necessary. We make the decision by taking a transform over a window including the major peak, from Gate 100 to Gate 104. This transform gives the amplitude/phase functions of Figure 2.15. This is a sufficiently good approximation of the pattern of two interfering scatterers to use the corresponding algorithm for determining the crossrange positions of the two scatterers [1].

2.8 SUMMARY

We have discussed the problems of motion compensation when a target is not moving in a plane or when the target is not sufficiently rigid for normal ISAR imaging. In these generalized cases, which are of considerable interest in practice, we need new motion compensation procedures. Since forming a "focused" ISAR image becomes irrelevant in these situations, we must instead focus those responses needed for target identification. This is not easy because we must start at a stage where the responses are smeared over many crossrange gates. However, as demonstrated above, the problem is solvable. In situations where it does not appear solvable, we have little choice but to

make it solvable via reducing the imaging time and crossrange resolution. The required processing procedures evidently are rather complicated, but identification of moving targets under general conditions is not a simple problem, and hence does not appear solvable with simple methods.

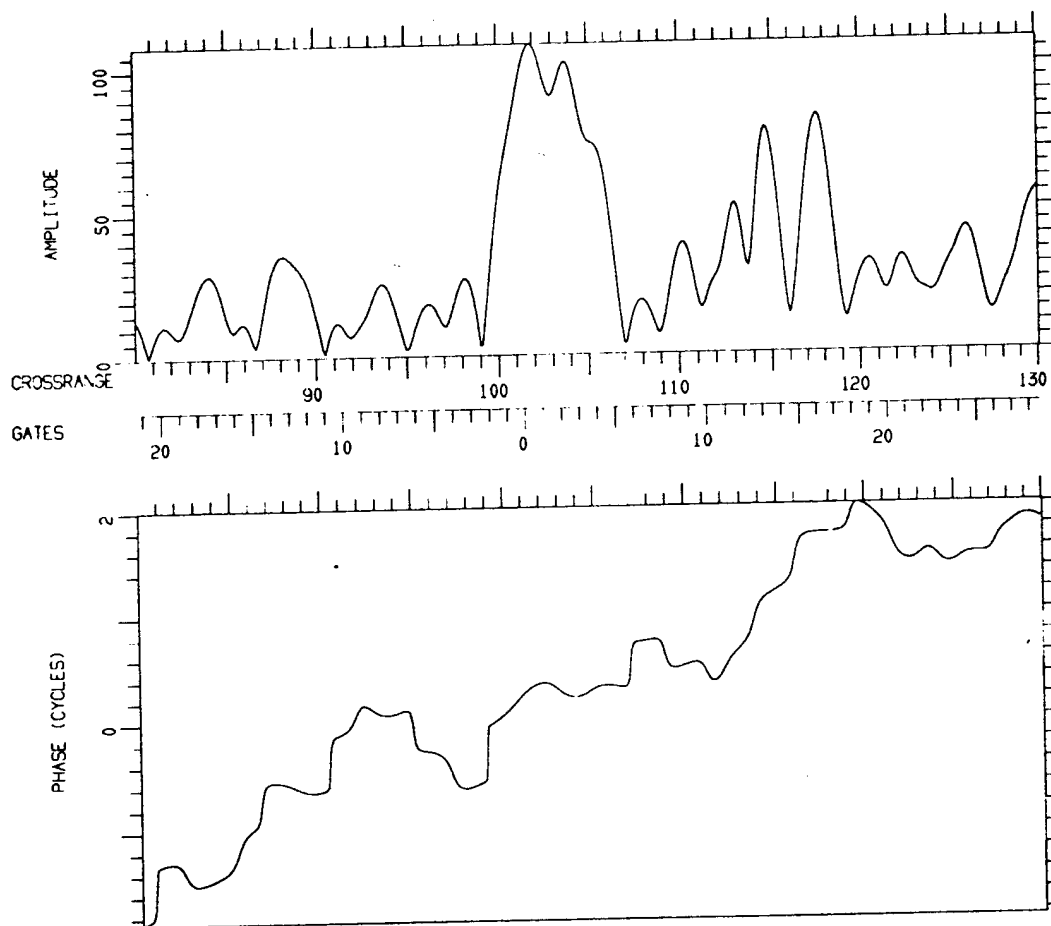


Figure 2.12. Image Cut in Range Gate 36.4.

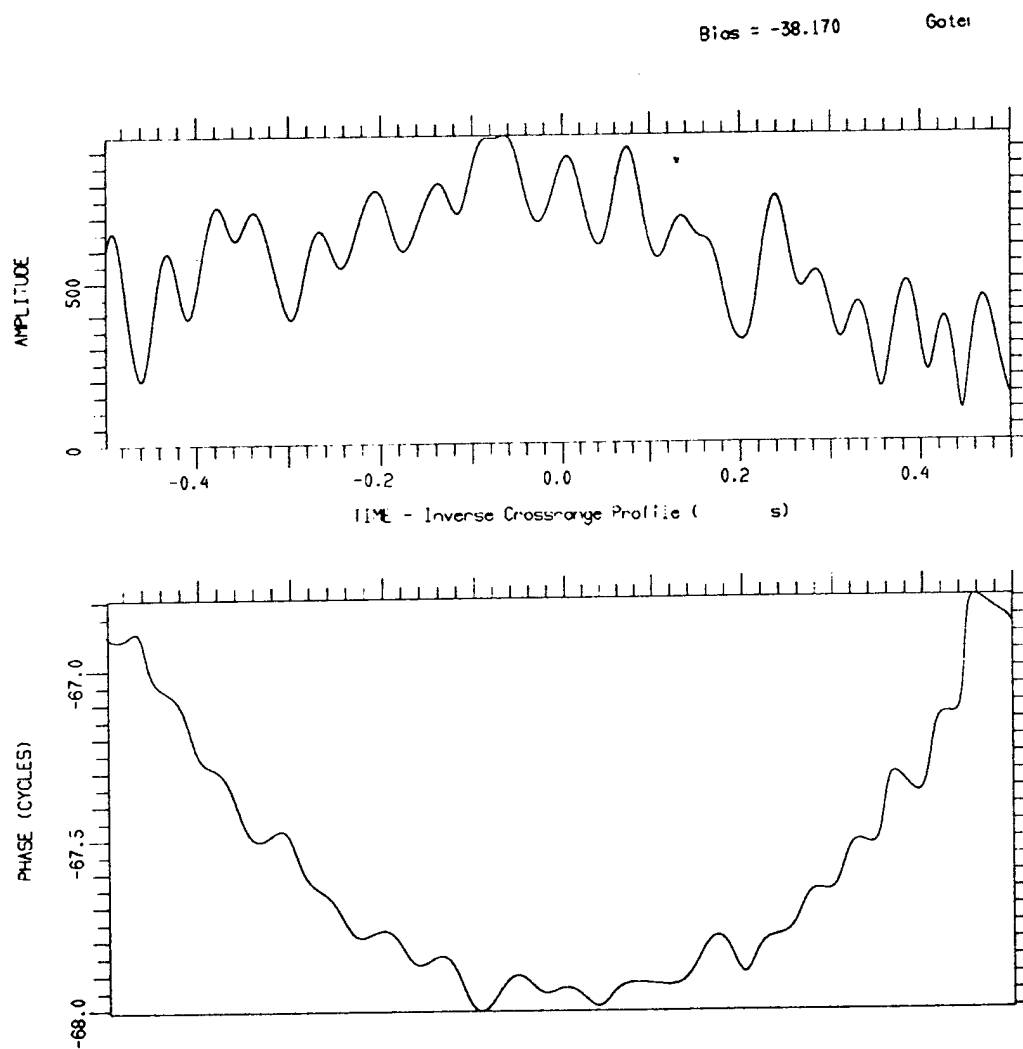


Figure 2.13. Phase Function for the Response in R40.1/C90.3.

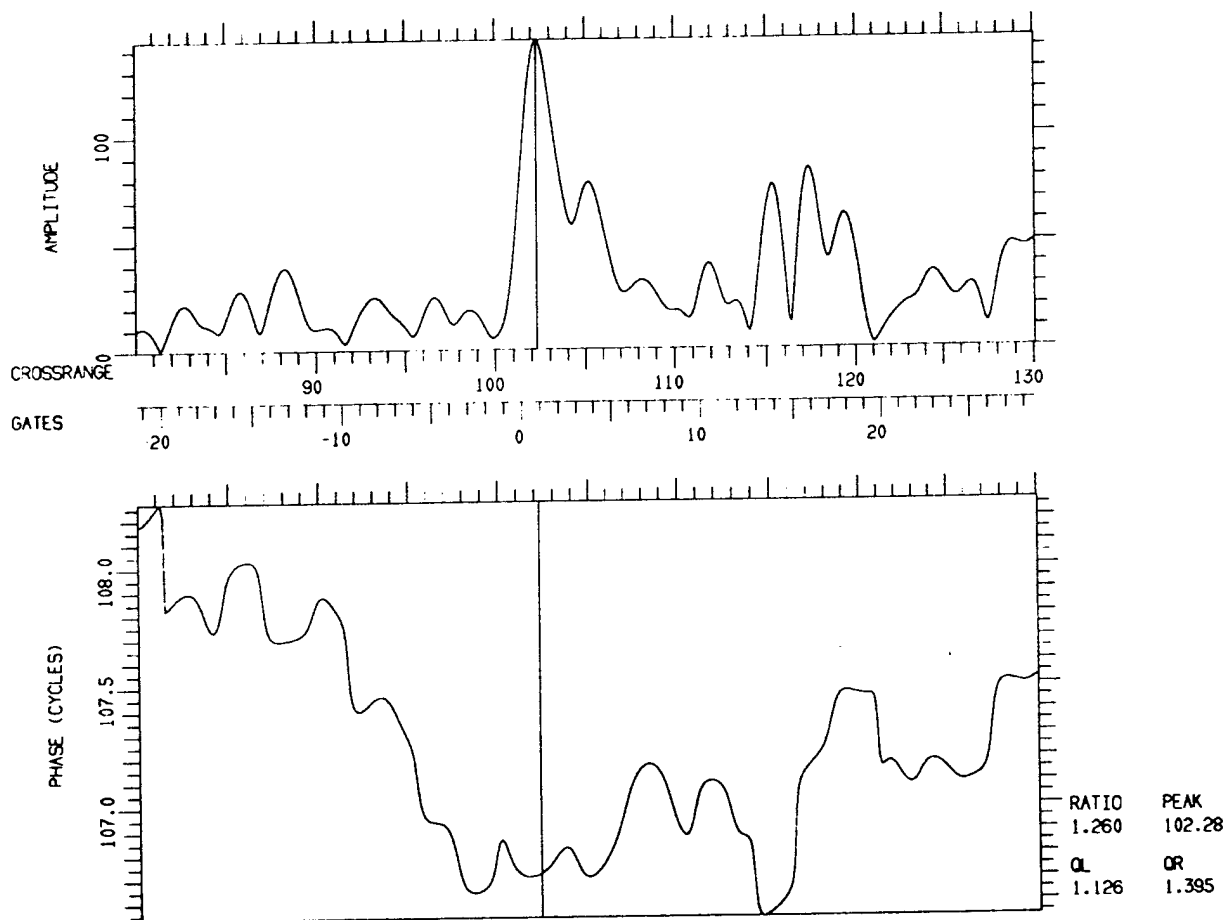


Figure 2.14. Image Cut of Figure 2.12 After Compensation.

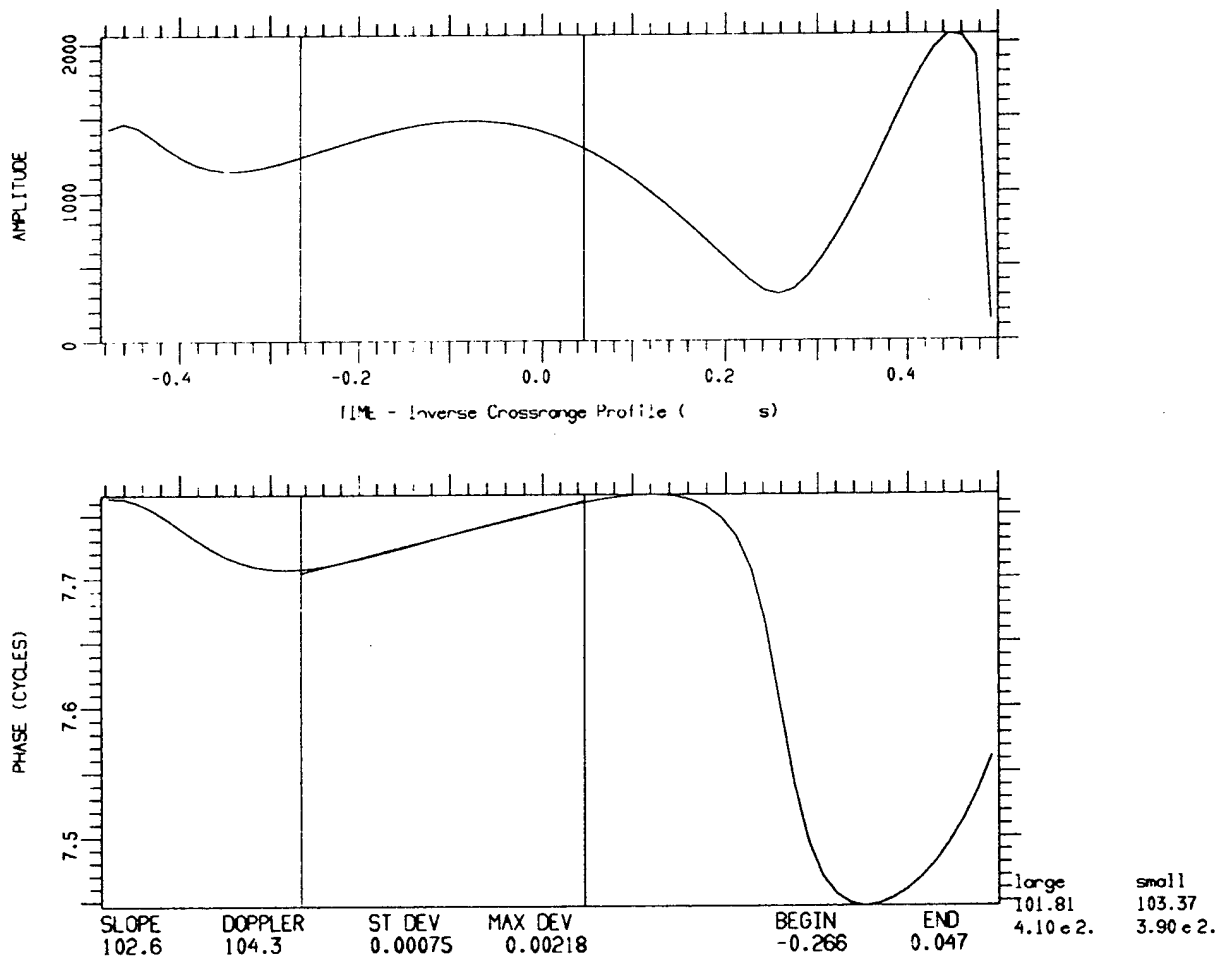


Figure 2.15. Transform of the Major Peak of Figure 2.14.

3. IDENTIFICATION OF A TURNING VEHICLE

3.1 SCOPE OF THE TREATMENT

As already stated, it is our belief that for reliable identification of a man-made target from its radar image one must be able to locate responses from specific target features. If one wants to perform these detailed measurements, then too much essential information is lost if only the intensity image is utilized; the analysis procedures must utilize the complex image, amplitude and phase [1]. Although the utilization of the image phase requires a good motion compensation, in the case of stationary ground vehicles this requirement is met by the now standard motion compensation methods for SAR. If the ground vehicle is moving, on the other hand, an additional motion compensation must be applied to the image of the vehicle. This motion compensation ranges from relatively easy to very difficult, depending on the type of vehicle, the kind of road or terrain on which it is moving, and the clutter environment. After one has performed a good motion compensation, the complex image must be analyzed to extract the positions and characteristics of the vehicle features, for correlation with a database of the vehicles of interest.

In Section 2 we developed motion compensation procedures for the case where three-dimensional motion effects and the consequences of target flexing are important. The primary intent of these procedures is to allow the measurement of the positions of the observable target features. In this section we want to show how this can be done successfully. Judging the success of the motion compensation and of the measurement of the feature positions requires comparing the measurement results with the actual feature positions on the target. This is the most important ingredient in target identification, and is treated in this section. It is clear, however, that target identification requires more. First, we must fully automate the procedures for measuring feature positions and comparing these with the database. Second, to the extent possible we must utilize characteristics of target features other than their positions, again in an automated manner. Third, we must examine diagrams and photographs of all targets of interest in order to determine which features will be observable under given circumstances. Of all these problems, in the following we treat only the

basic problem of measuring feature positions and comparing measured and predicted positions. As already noted, the example of the turning Winnebago RV is a relatively benign case for moving ground vehicles.

3.2 THE VEHICLE IN OUR EXAMPLE

The vehicle is a Winnebago recreational vehicle, and it is turning on a wide paved surface. The SAR system is designed to achieve high crossrange resolution on stationary vehicles. Since the aspect angle of the turning Winnebago changes much faster than that of a stationary vehicle, we have an excess imaging time as long as we do not want to achieve a crossrange resolution much better than that on stationary vehicles. This excess imaging time allows us to analyze the vehicle motion and, if desirable, to select the imaging time for which generating and analyzing the image is easiest. Since the turn is relatively slow and smooth, we do not have severe bouncing, yawing, pitching, and rolling motions, so that the crossrange smearing of the image is small. On the other hand, the large height of the vehicle and its not-so-rigid construction imply that the consequences from the three-dimensional motion and flexing may be significant. These consequences are magnified by the relatively short radar wavelength of 2 cm.

A survey plot of the SAR scene containing the turning RV is shown in Figure 3.1, with the vehicle image marked by an arrow. The background below -26 dB relative to the highest peak is not shown in the image. The imaging time is 2.7 s for this figure. As Figure 3.1 indicates, there are clutter regions with cross sections comparable to that of the vehicle in the vicinity. Because during the turn the vehicle image can easily be shifted into these clutter regions, and because even clear-area clutter may influence the first stages of the motion compensation, it appears preferable to use the data after clutter cancellation. The corresponding intensity image is shown in Figure 3.2. The strong clutter has been reduced sufficiently to allow amplifying the vehicle responses so that the entire smeared image becomes clearly visible.

A subimage without clutter cancellation, again using an imaging time of 2.7 s but 3 s later than in Figure 3.2, is shown in Figure 3.3. Both the range and the crossrange intervals have been greatly reduced. The vehicle now is viewed at broadside. As expected, the image of the vehicle remains in the

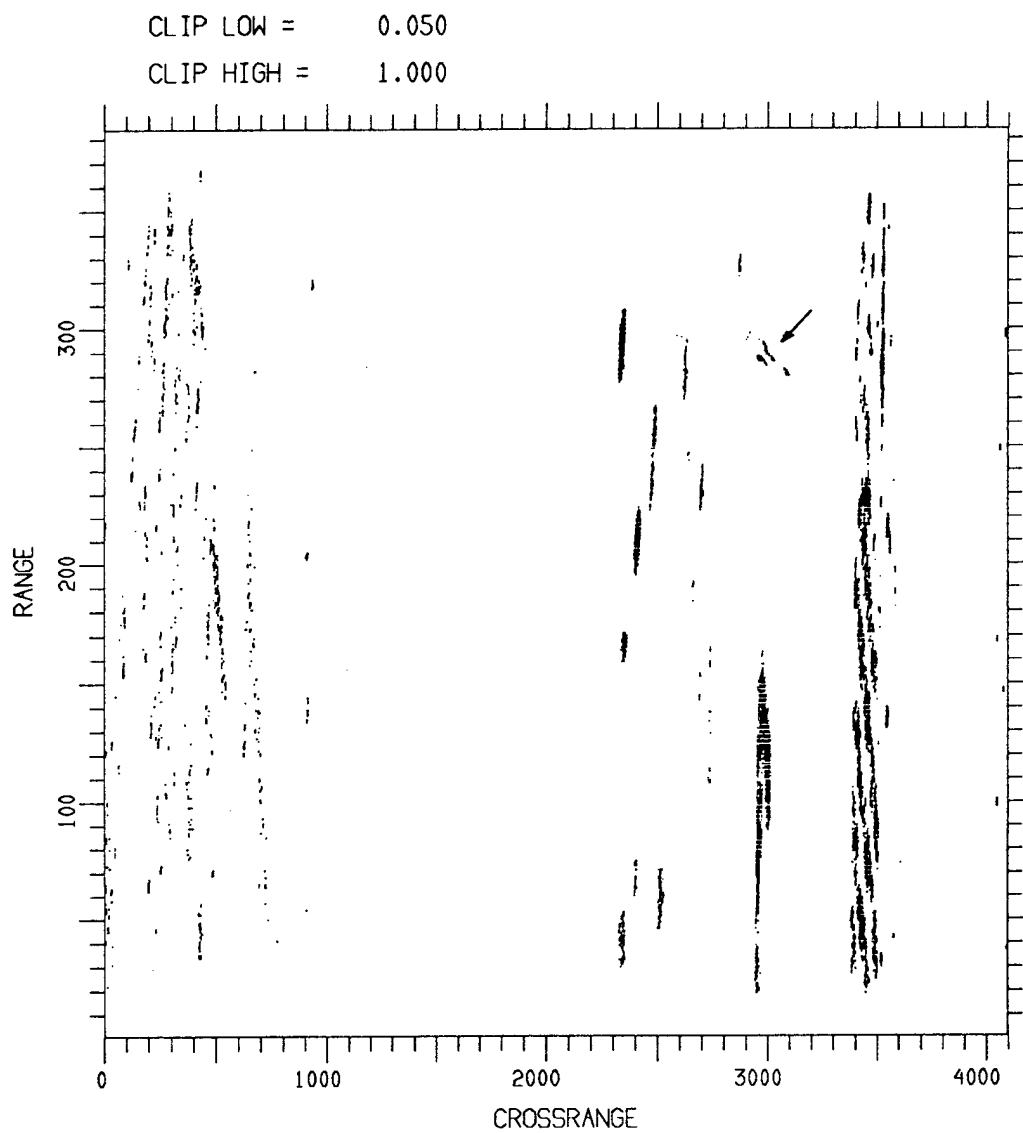


Figure 3.1. Survey Plot of the SAR Scene with the Vehicle.

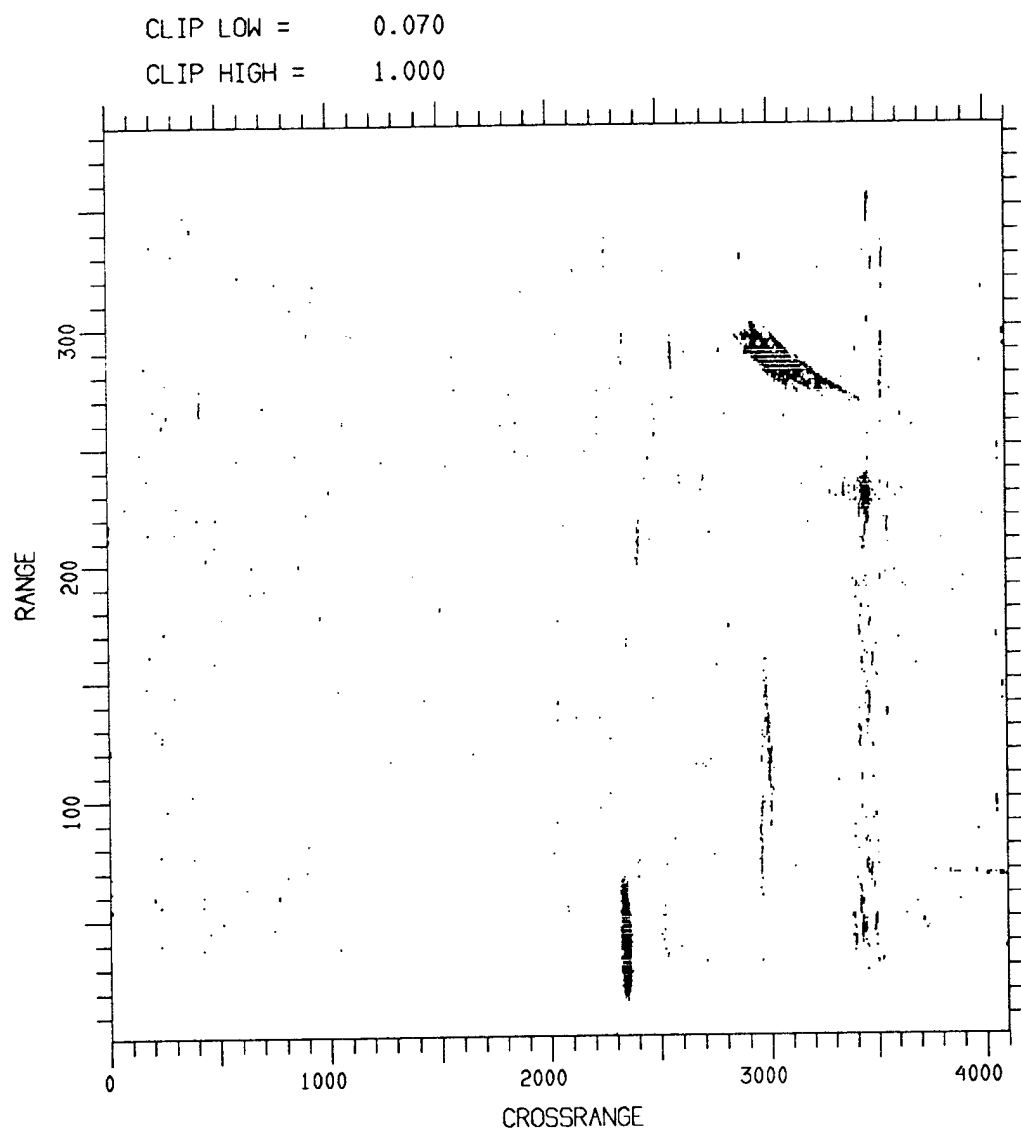


Figure 3.2. Survey of the SAR Scene After Clutter Cancellation.

CLIP LOW = 0.050
CLIP HIGH = 1.000

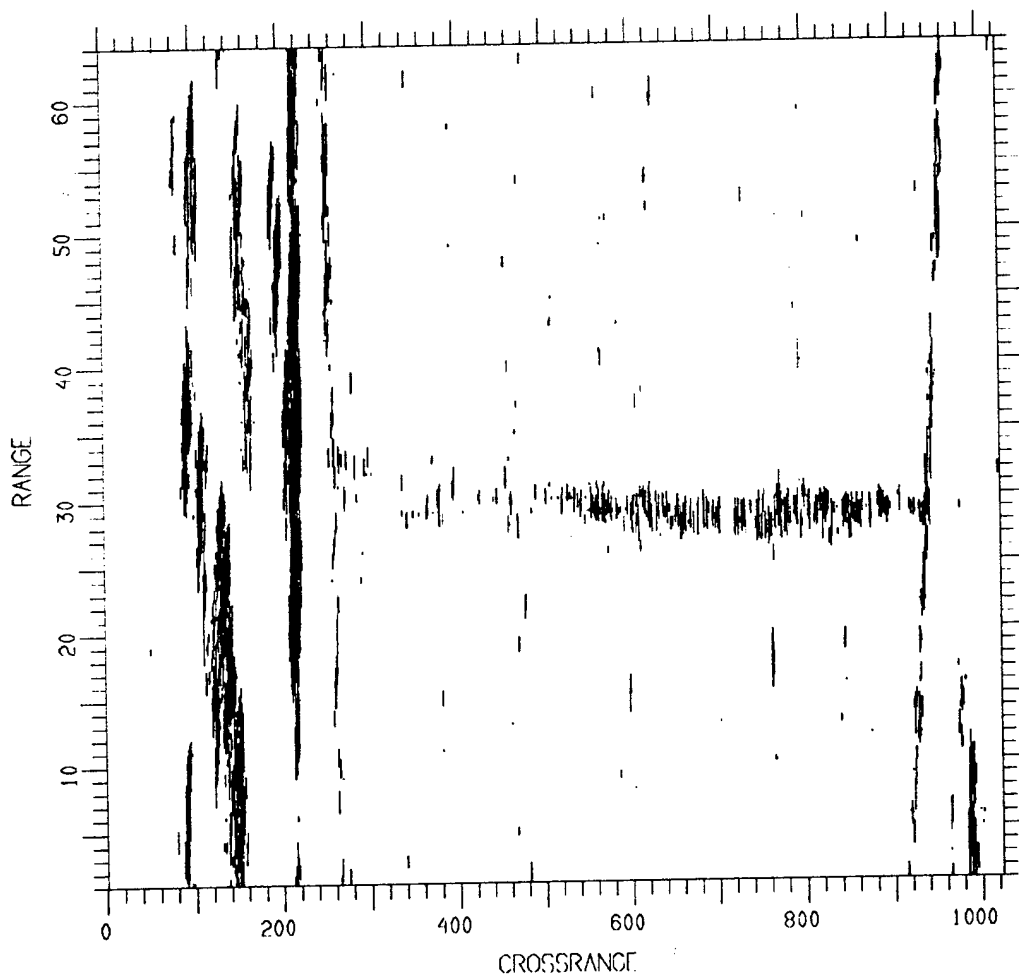


Figure 3.3. Survey Plot 3 s Later, Without Clutter Cancellation.

clear area where it is turning. Hence, at broadside where clutter cancellation does not work, we do not need it. This statement applies only as long as the rolling motion of the vehicle is not so great that the image is so smeared in crossrange that it extends into the high-clutter region. If that should be the case, we face a difficult problem. Although the rolling high parts of the vehicle may be retained in the clutter cancellation process, those close to the ground will not.

A turning ground vehicle offers an opportunity not available with aircraft. The SAR system uses a dwell time long enough to obtain high crossrange resolution on stationary targets, and during this dwell time a turning vehicle may complete a large part of the turn. Thus one can track the vehicle in the image as it is turning, and from the track determine the aspect angle as a function of time. This can be done much more accurately than for an aircraft, which in an unsteady flight can have aspect angle variations too fast to be measured accurately by the tracking radar. If we measure the aspect angle as a function of time, we can determine the crossrange scale of the ISAR image. The scales for both range and crossrange then are known, so that true vehicle dimensions and feature positions can be measured independently of the process of matching the measured data to the predicted data in the database.

3.3 THE BEHAVIOR OF THE VEHICLE

For a turning vehicle the available imaging time is much more than needed to achieve good crossrange resolution. Thus we could select some short interval within the dwell time of the radar, apply the appropriate motion compensation to the image and then to the individual responses, and measure the feature positions. However, with a turning vehicle that is tall and not completely rigid the motion behavior will vary over the available dwell time, and there will be good times for analyzing the responses and bad times. Thus, if an excess imaging time is available, we will first determine the best imaging interval. To demonstrate the process of selecting a good imaging interval, we will choose an interval much larger than needed, and show how to select good intervals for imaging.

We face the same problem as discussed earlier with respect to the compression of individual responses. We must not choose a motion compensation in

which flexible splines are applied, because they can introduce so much spurious motion that the actual motion of the vehicle is obscured. On the other hand, if we use only linear or quadratic fits in the range centroid and Doppler centroid compensation steps, the responses may well be smeared to such a degree that no response allows us to measure the motion behavior of the scatterer. The only obvious remedy then is to reduce the interval over which the motion behavior is to be measured, so that less flexible spline functions still do not cause too much spreading of the responses. We must compromise between the spreading of the responses due to a poor motion compensation and the spreading caused by the loss of crossrange resolution. Of course, a shorter interval does not provide as much information on the target behavior as a long interval. Thus we may have to analyze two or more consecutive intervals to obtain insight into the target behavior.

We select an initial imaging interval that covers an aspect angle change in the order of 40° , with aspect angles not too close to zero and to broadside, using an interval of 2.7 s for analysis of the motion behavior. The corresponding image of the vehicle as it appears in the SAR scene after Displaced Phase Center Aperture (DPCA) clutter cancellation is shown in Figure 3.4. Although in this instance it is again not necessary to use the data after clutter cancellation, because the range rate of the vehicle does not superpose its image on a region with high clutter, since clutter cancellation is available we make use of it. The length of the vehicle is 24 ft and the aspect angle is non-zero, yet in the image the range extent of the vehicle is more than 30 ft. This means that the vehicle is moving over a considerable number of range cells during the imaging time. The shape of the image thus is dominated by the translational motion of the vehicle, which implies that the other motion components are not so severe as to cause a very large spreading of the vehicle image in crossrange. We need to test first whether a crude motion compensation, as we must apply at this stage, will keep each scatterer sufficiently well within its range gate and reduce the crossrange smearing sufficiently to permit measurements of the motion behavior. If the answer should be no, we would have to reduce the imaging time.

We apply range centroid and Doppler centroid tracking, using only linear fits. Any residual motion of nonlinear Doppler thus will be due to the vehicle motion rather than the motion compensation. As always, we will for

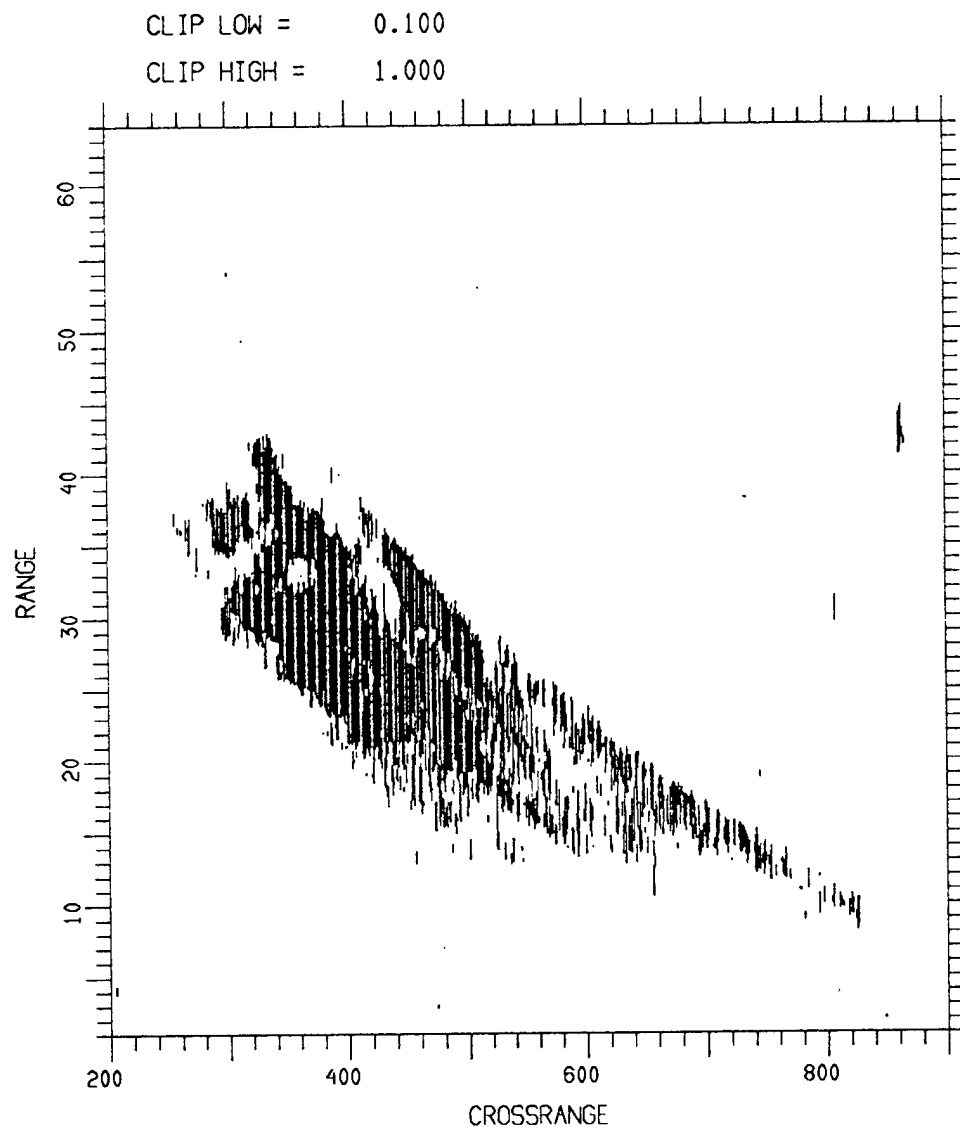


Figure 3.4. Vehicle Image in the SAR Scene.

all other steps present the images in peaks plot form. The peaks plot corresponding to the intensity image of Figure 3.4 is shown in Figure 3.5. A comparison with Figure 3.4 shows the reduced range and crossrange spreads of the image. We now take image cuts in the range gates of the major responses, and Fourier transform the complex responses. If a resulting amplitude function is constant over an extended time interval, the associated phase will describe the motion of the associated scatterer. If this test is successful, we can analyze the 2.7 s image. If not, then the imaging time must be shortened.

The best response which can be found is that in Range Gate 31, for which the image cut is shown in Figure 3.6, amplitude function at the top and phase function at the bottom. Because of the crude motion compensation, the response is smeared over the interval marked by the two crosshairs. The transform of the complex response over the indicated window is given in Figure 3.7. Over the last two thirds of the imaging interval, the amplitude is sufficiently constant (no deep breaks) to allow measuring the motion behavior. The observed phase change gives directly the residual range wander of the scatterer, with a change of one cycle corresponding to a range change of half a wavelength. However, we cannot measure the motion behavior over the first third of the interval. Moreover, in the entire image we cannot find another response that would allow any measurement of the motion of other parts of the vehicle. The imaging time thus is too long.

We reduce the imaging time to the first 1.5 s, with the new peaks plot of the crudely compensated image (range and Doppler centroid tracking) shown in Figure 3.8. When the Fourier transform is taken of the same response as used for Figure 3.7, we obtain the amplitude and phase functions of Figure 3.9. Since the amplitude has no deep breaks and the motion compensation used linear fits, the variation of the phase function now represents the actual motion of the scatterer. Although the phase fluctuates only by somewhat more than half a cycle (range motion of a little more than a quarter wavelength), this is far too large a residual motion for a usable image.

From Figure 3.9 we learn that the scatterer in Range Gate 31 moves back and forth roughly sinusoidally, with about two cycles over the imaging time of 1.5 s. This could be due to the motion of the vehicle, or it could be the shifting motion of the phase center of a complicated scatterer (unlikely in

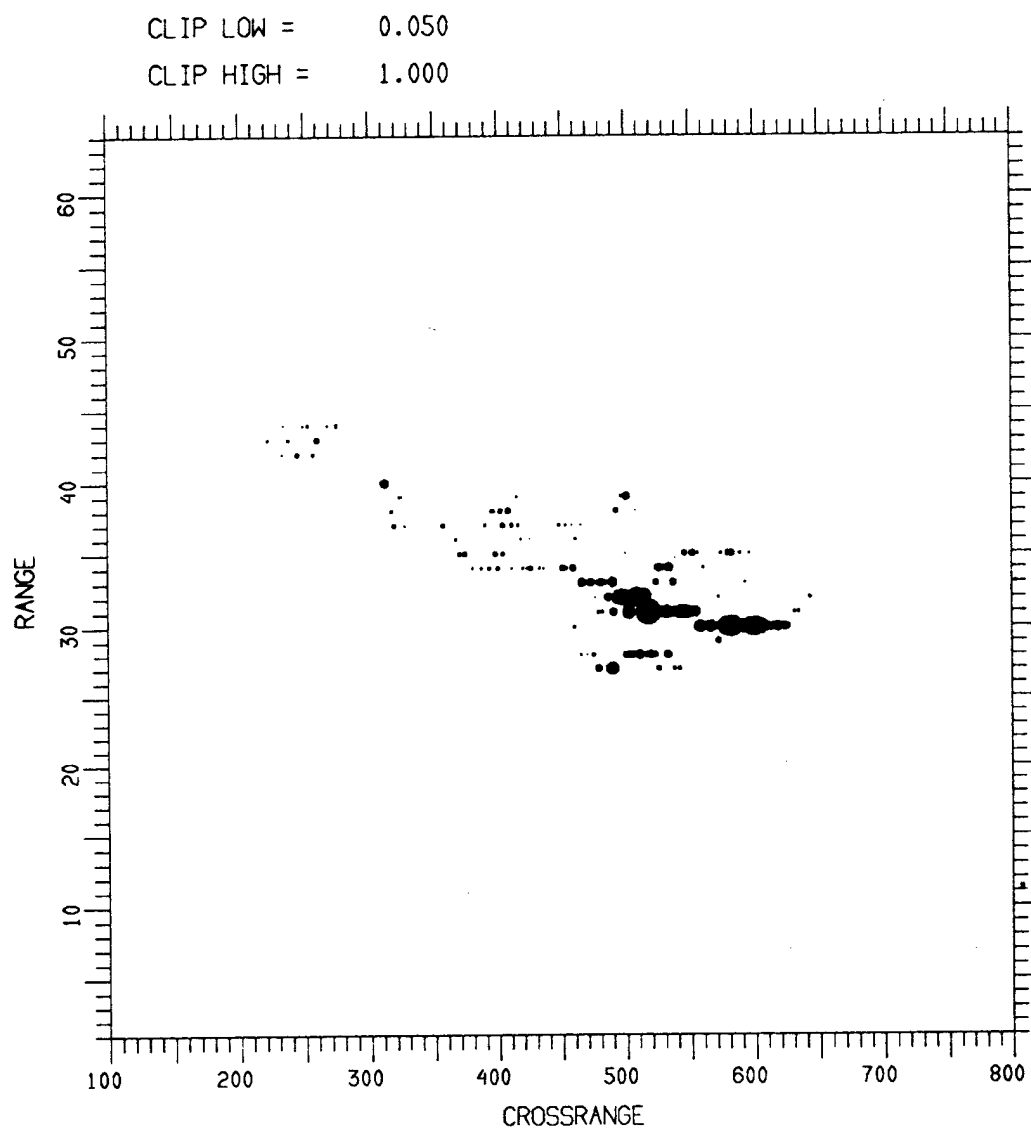


Figure 3.5. Peaks Plot After Crude Motion Compensation.

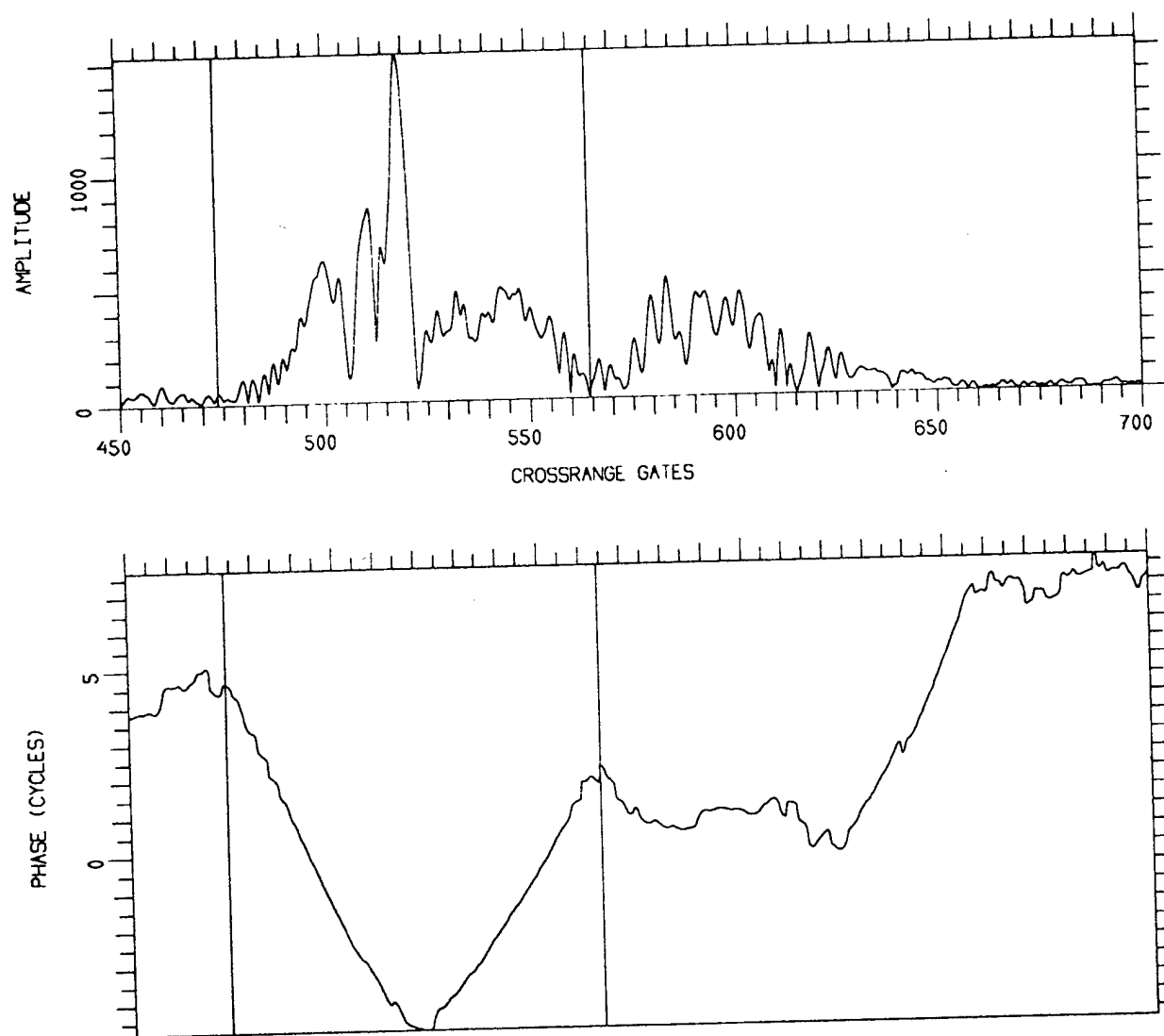


Figure 3.6. Image Cut in Range Gate 31.

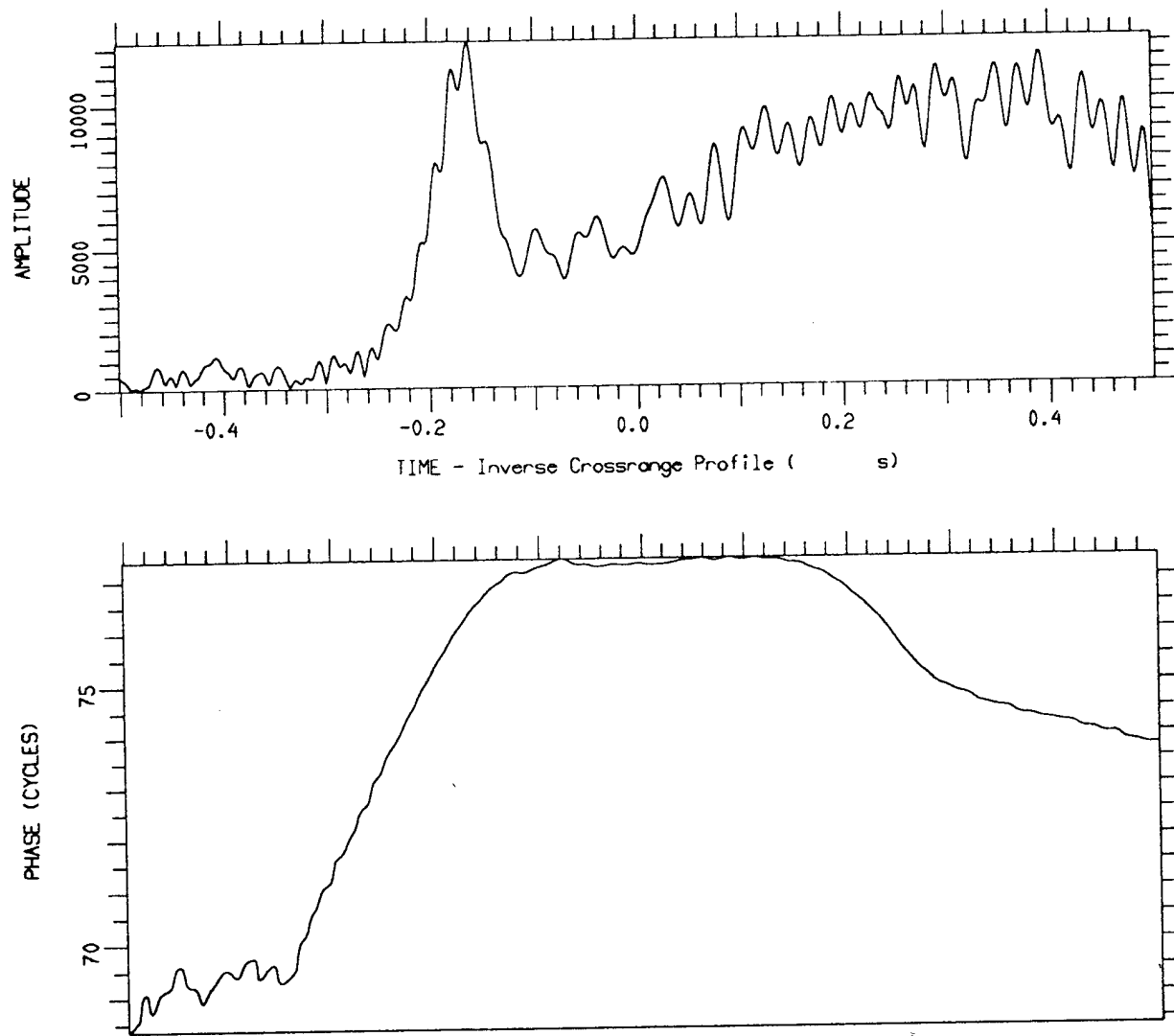
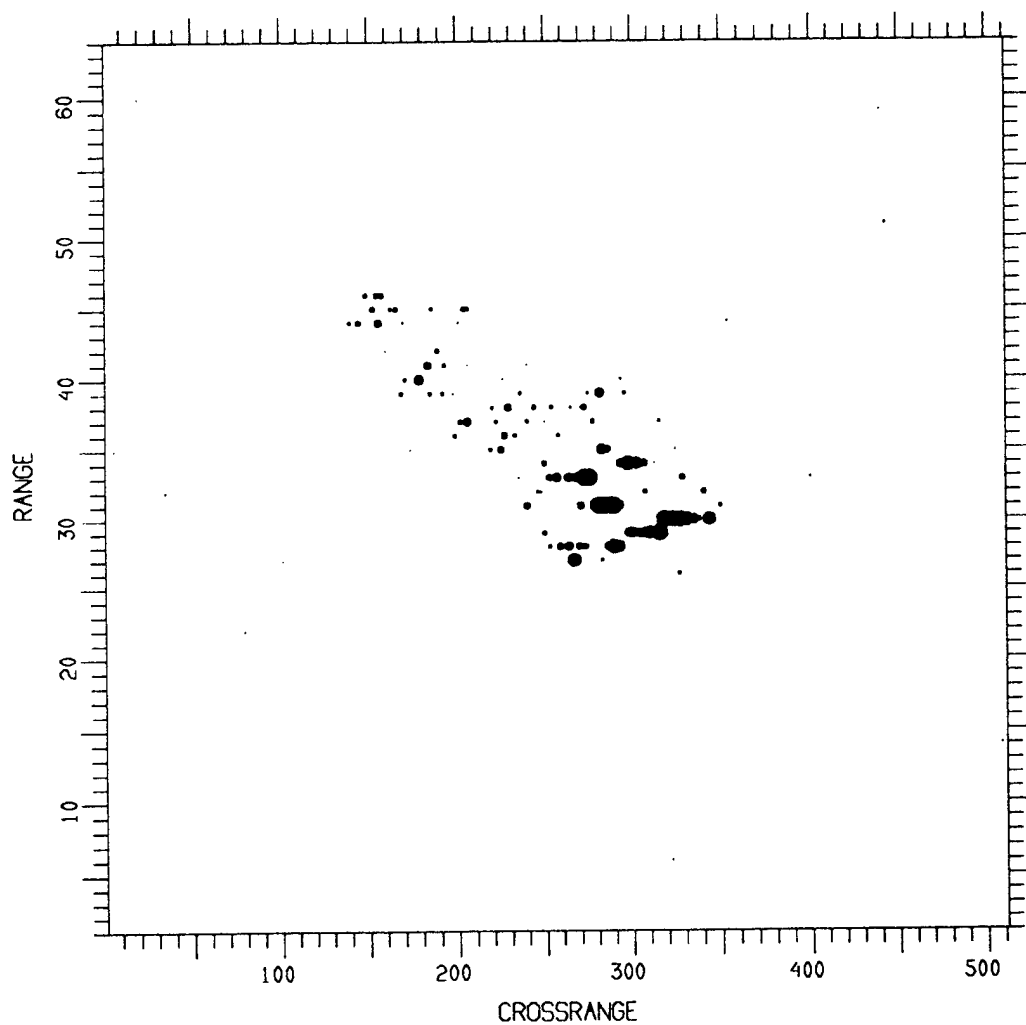


Figure 3.7. Transform Over the Window of Figure 3.6.

CLIP LOW = 0.020

CLIP HIGH = 0.200



**Figure 3.8. Peaks Plot With Crude Motion Compensation,
Reduced Imaging Time.**

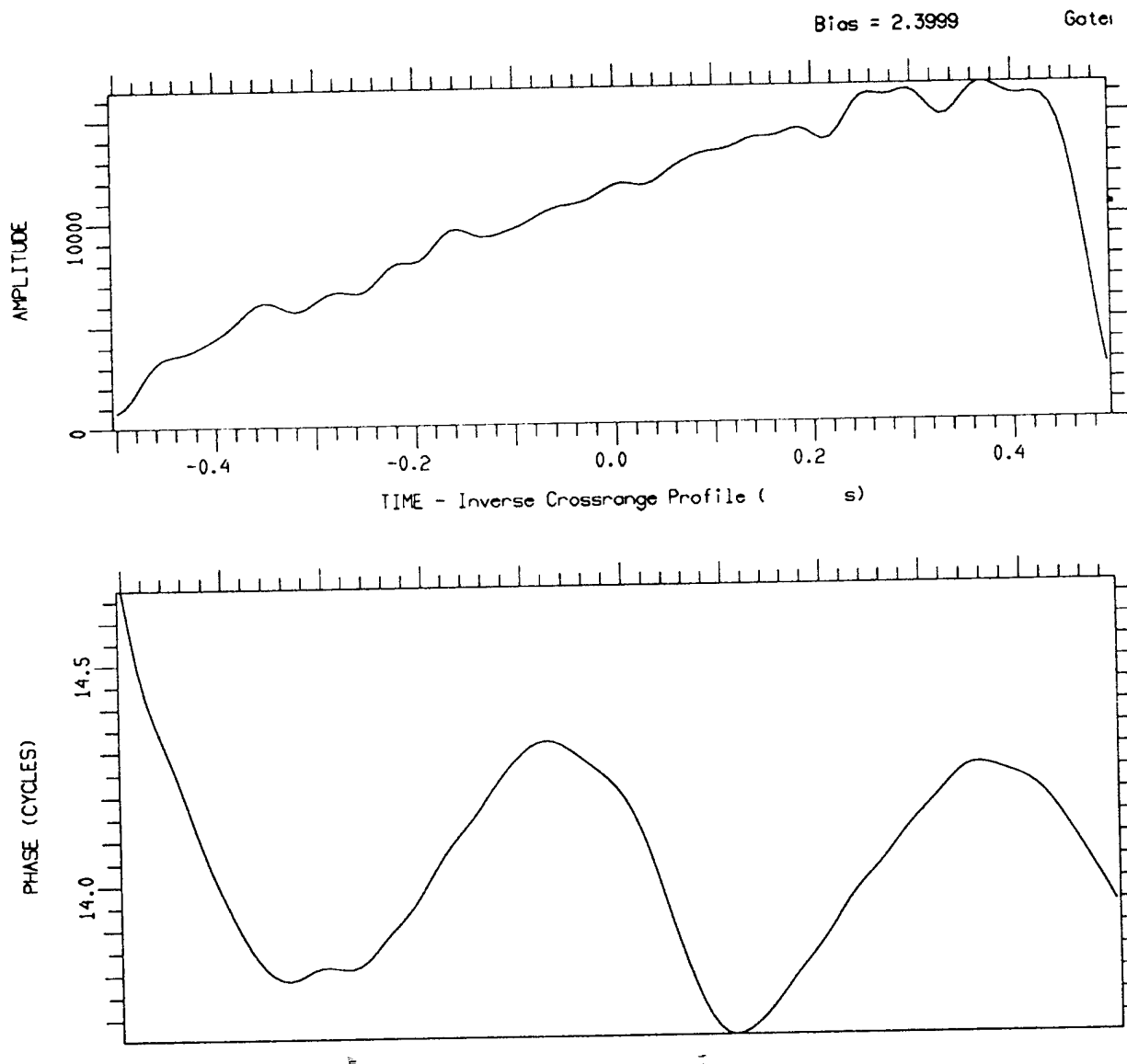


Figure 3.9. Transform of the Smeared Response in Range Gate 31.

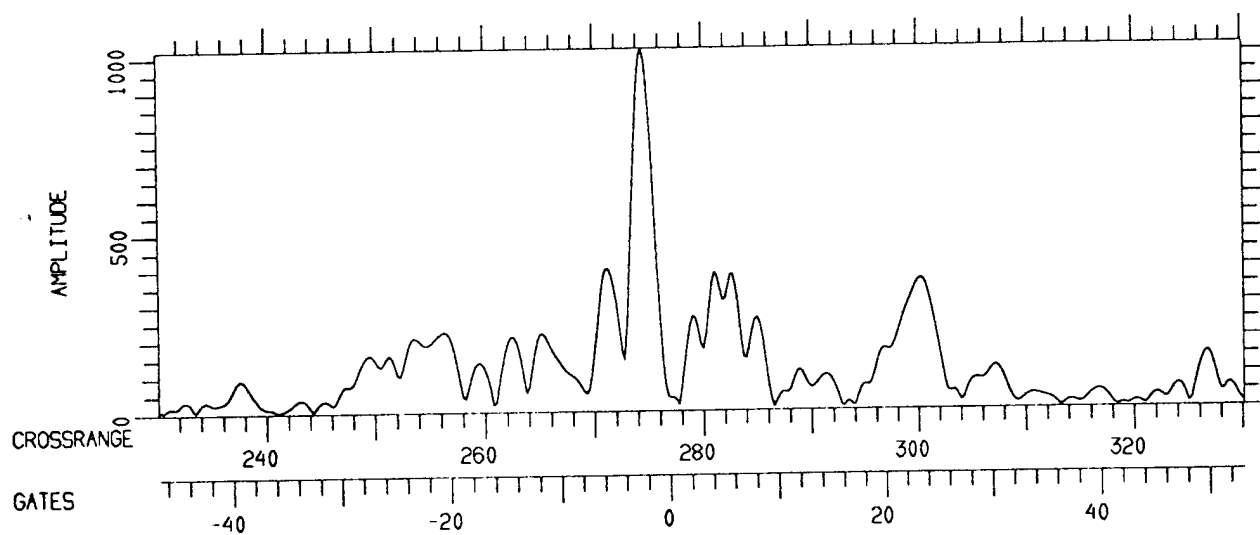
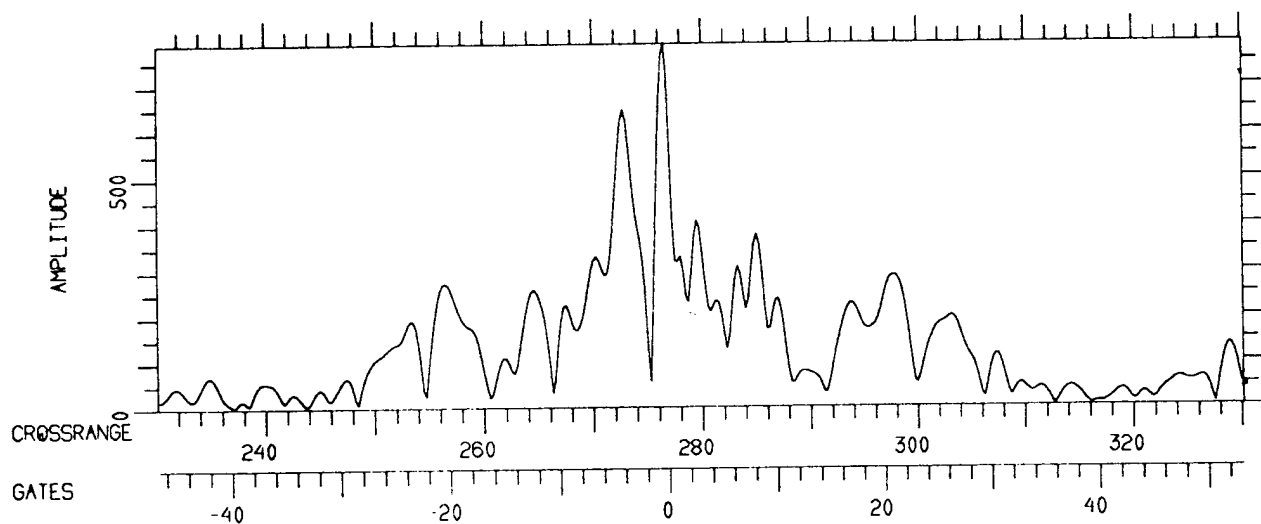
the case of two motion cycles). We test for this by considering nearby range gates. If we use the phase function of Figure 3.9 to compensate these range gates, the responses will be further smeared if it is a phase center motion unique to one specific scatterer. In case of a vehicle motion the responses will be compressed.

We choose an image cut in Range Gate 33, about 2 range gates away from that of Figure 3.9. The amplitude function for this image cut is shown in Figure 3.10, Top. There appears to be a smeared response centered in about Crossrange Gate 276 in the top plot. After applying the phase compensation derived from Figure 3.9, we obtain the amplitude function at the bottom of Figure 3.10. The response clearly is much more concentrated, but far from perfectly. We conclude that the new scatterer is moving almost like that in Range Gate 31, but not quite. The implication is that the phase function of Figure 3.9 does represent vehicle rather than phase center motion, but that the detailed motion characteristics change over the vehicle; that is, the vehicle must be bending or flexing. This can be tested by finding the phase function of a scatterer far removed, which should be quite different from that of Figure 3.9. However, with this type of crude motion compensation, a scatterer which remains in one range gate and whose spread response does not overlap too much with other responses could be difficult to find.

Figure 3.11 shows the transform of a response in Range Gate 40. Although deep amplitude breaks are absent only in the central part of the figure, so that the phase function gives a reliable indication of the scatterer motion only over that part, from a comparison with the phase function of Figure 3.9 it is clear that the scatterer motion is radically (for imaging) different. Hence we conclude that the vehicle has a significant flexing motion that will smear the responses in crossrange and will falsify the crossrange positions of the scatterers when the motion compensation is refined to give a focused image.

3.4 IMAGING OF THE VEHICLE

We stated earlier that imaging of a vehicle with three-dimensional motion and flexing is not of interest for target identification, and that identification must be based on individual responses. Nevertheless, we form images for orientation purposes. Even though a crude image resulting from range centroid



**Figure 3.10. Amplitude Function in Range Gate 33, Top;
After Compensation, Bottom.**

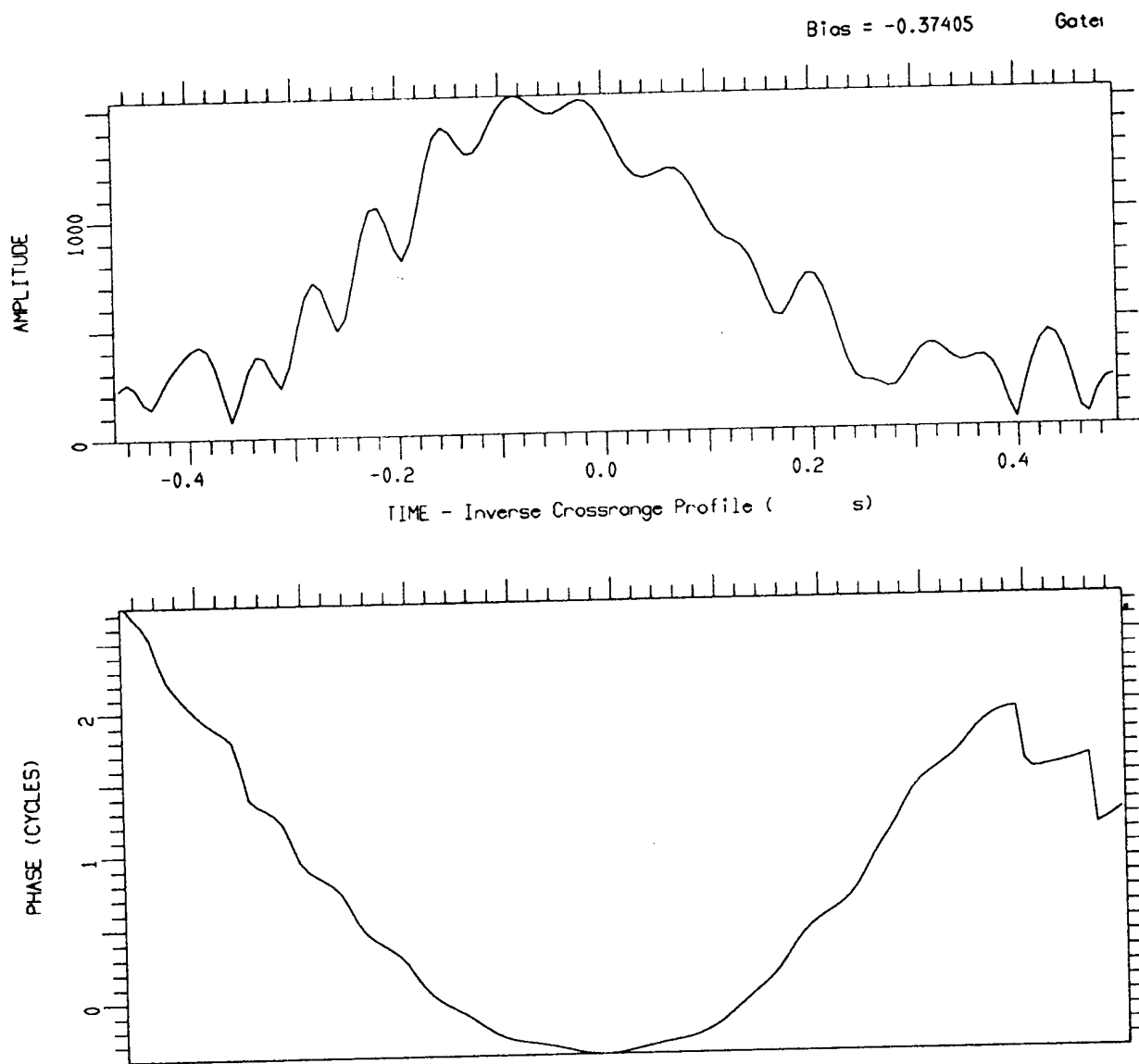


Figure 3.11. Transform of a Response in Range Gate 40.

and Doppler centroid compensation cannot be used for target identification, it can be used for selecting the major responses that are to be compressed for further utilization.

We use a template matching procedure to compare measured and predicted feature positions. This procedure translates and rotates the three-dimensional predicted positions, projects them into the radar observation plane, and varies the assumed crossrange resolution to optimize the match with the measurements. We will perform the procedure with three different images. The first image is formed centered at the normalized time of -0.06 s, where Figure 3.9 shows a stationary point for the flexing motion, so that the consequences should be minimal. We will repeat the imaging one flexing cycle later, at a normalized time of 0.37 s. This will show how quickly or slowly the observable vehicle features change with a change of the aspect angle. Lastly, we will form an image centered at a normalized time of 0.24 s, where in accordance with Figure 3.9 the flexing effects should be maximum. This will show whether or not these effects are serious. We choose imaging times so that crossrange resolution is approximately the same as range resolution, which is 1 ft.

To make an important point again, the fact that the flexing/bending of the vehicle may significantly falsify the crossrange positions of the scatterers (assuming that we can form a sufficiently focused image under these circumstances) does not imply that crossrange resolution is useless. By resolving responses in crossrange, we can perform more accurate measurements of the range positions of the scatterers, and the range position of a scatterer is the primary measurement for target identification. Nevertheless, if we can observe at least one full cycle of the bending motion for all scatterers, we should do so in order to eliminate the crossrange error due to flexing. If we cannot do so, then we should choose the imaging time so as to minimize the consequences of flexing.

We may not be able to satisfy all conditions and implement the approach to full theoretical satisfaction. For example, Figure 3.9 shows a fluctuating phase, whereas for the scatterer of Figure 3.11 the phase varies in about a quadratic manner. An imaging time centered on the maximum of the phase function near time zero in Figure 3.9 will also be a good choice for the scatterer of Figure 3.11, but at the time of the second maximum the phase in

Figure 3.11 is changing roughly linearly, implying a scatterer with about constant range rate. This amounts to a translation of the scatterer response in crossrange. If we have no choice but to use the second imaging time, we must place less value on the measured crossrange position of this scatterer than on its range position. Again, the primary measurement is that of the range position. This still does not imply that range resolution alone would be satisfactory, because without sufficient crossrange resolution we cannot measure range position accurately. The point is important enough to bear repeating.

By cutting out the appropriate time segment of the data used for the image of Figure 3.8, we obtain Figure 3.12. We repeat the same imaging by shifting the center time to the next maximum of the phase cycle of Figure 3.9, which gives the image of Figure 3.13. A comparison of Figures 3.12 and 3.13 shows little change for the relatively weak scatterers on the side of the vehicle, but more significant changes for the responses that are strong in Figure 3.12. This fact already indicates that these may be spurious sideband responses, because these change very rapidly with aspect angle. The third vehicle image is shown in Figure 3.14. We have to wait for the positional match to determine how significant the changes are; that is, to determine how important it is to select the best imaging time.

The tests we have performed so far show that the turning motion of the vehicle allows achieving a good crossrange resolution in a time short compared with the motion cycle of the vehicle, in this instance dominated by bending because the vehicle is turning smoothly. Thus it is possible to obtain a good quality image without many of the motion compensation steps that often must follow the crude compensation [1], such as the Doppler tracking of an individual scatterer, phase tracking of two scatterers, and polar format processing. However, before analyzing the images we did apply a fine phase compensation, removing phase curvature common to the strongest image peaks. We do not show the images with fine phase compensation because to the eye the (intensity) peaks with and without the fine phase compensation are indistinguishable.

3.5 POSITIONAL MATCHES

If each dot in the peaks plot represented the position of a scatterer on the vehicle, we could measure the positions of the peaks and correlate the

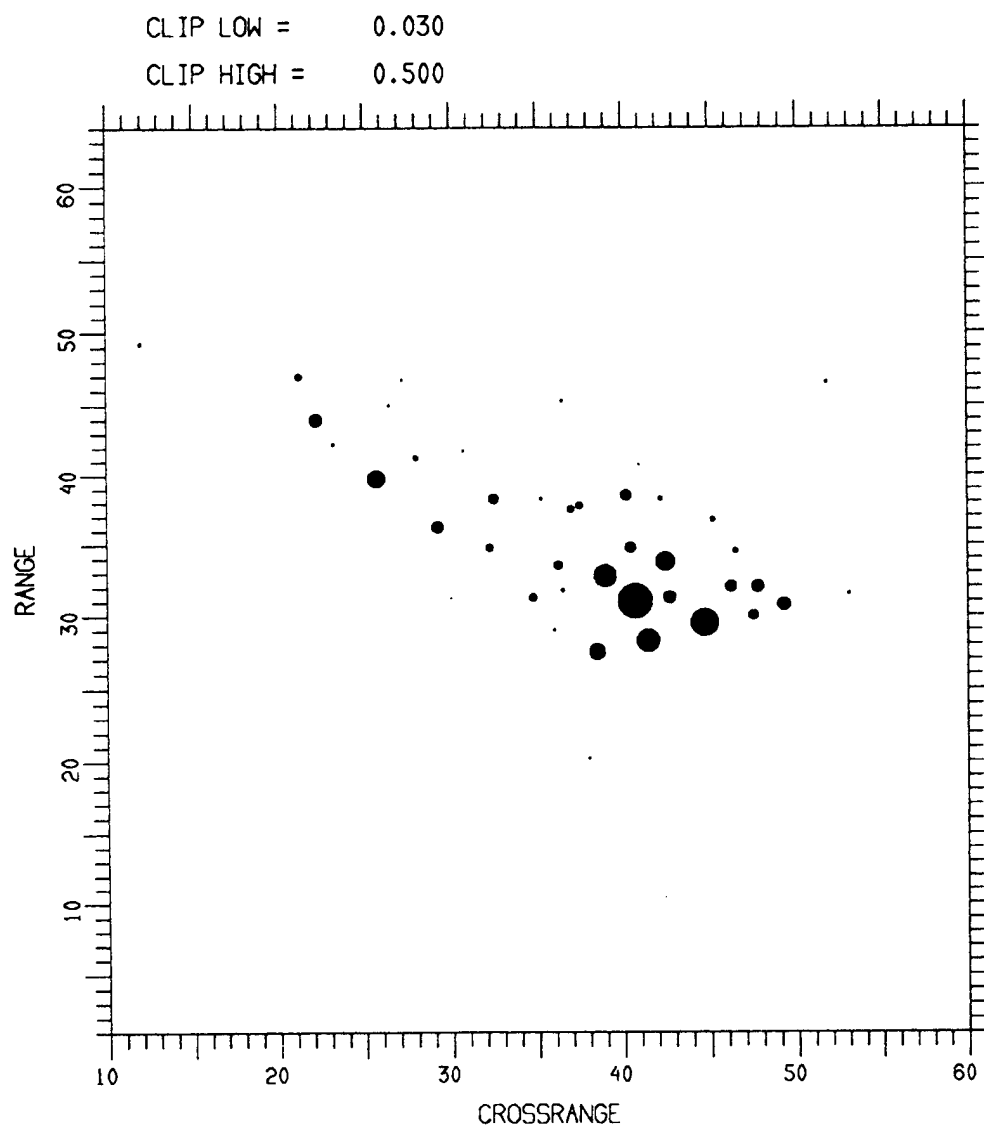


Figure 3.12. First Vehicle Image.

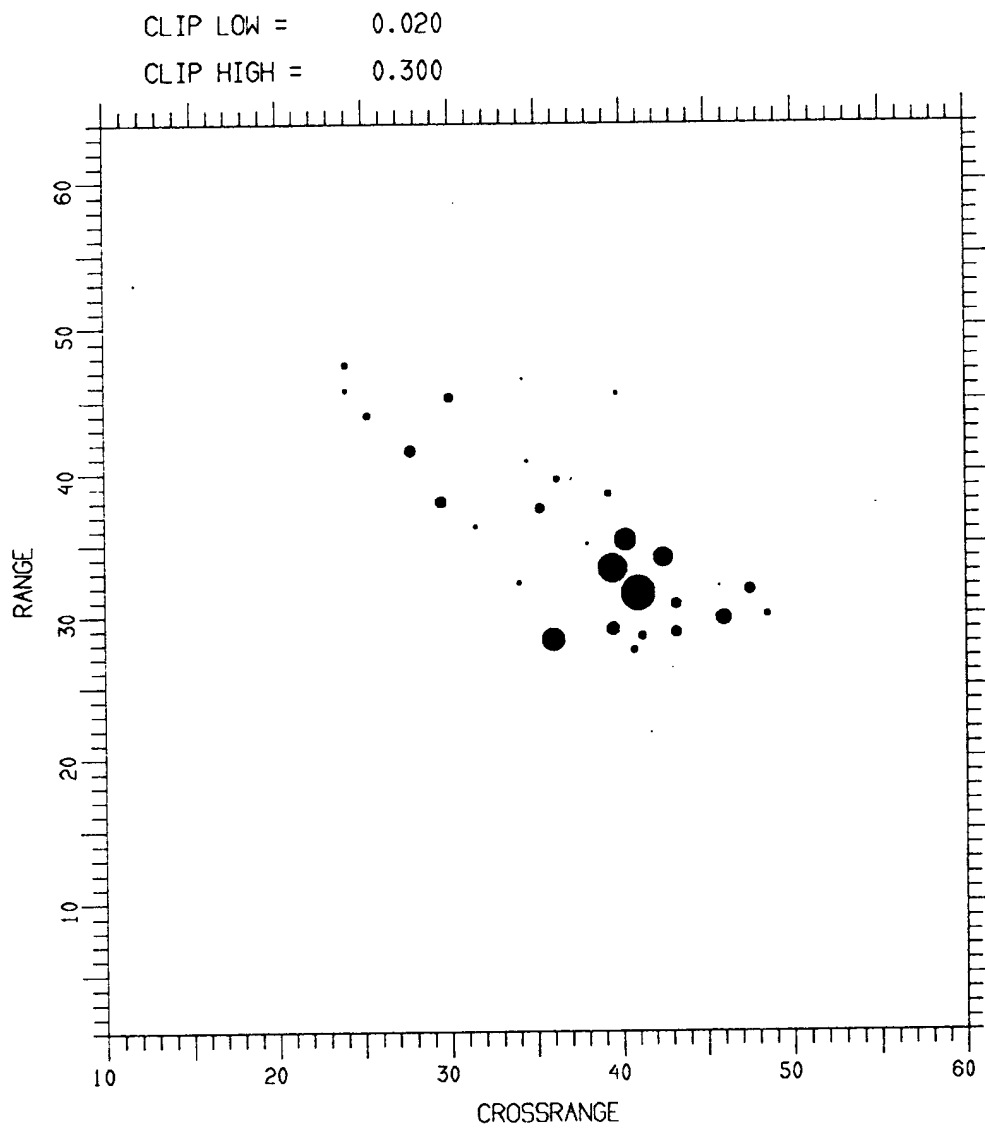


Figure 3.13. Second Vehicle Image.

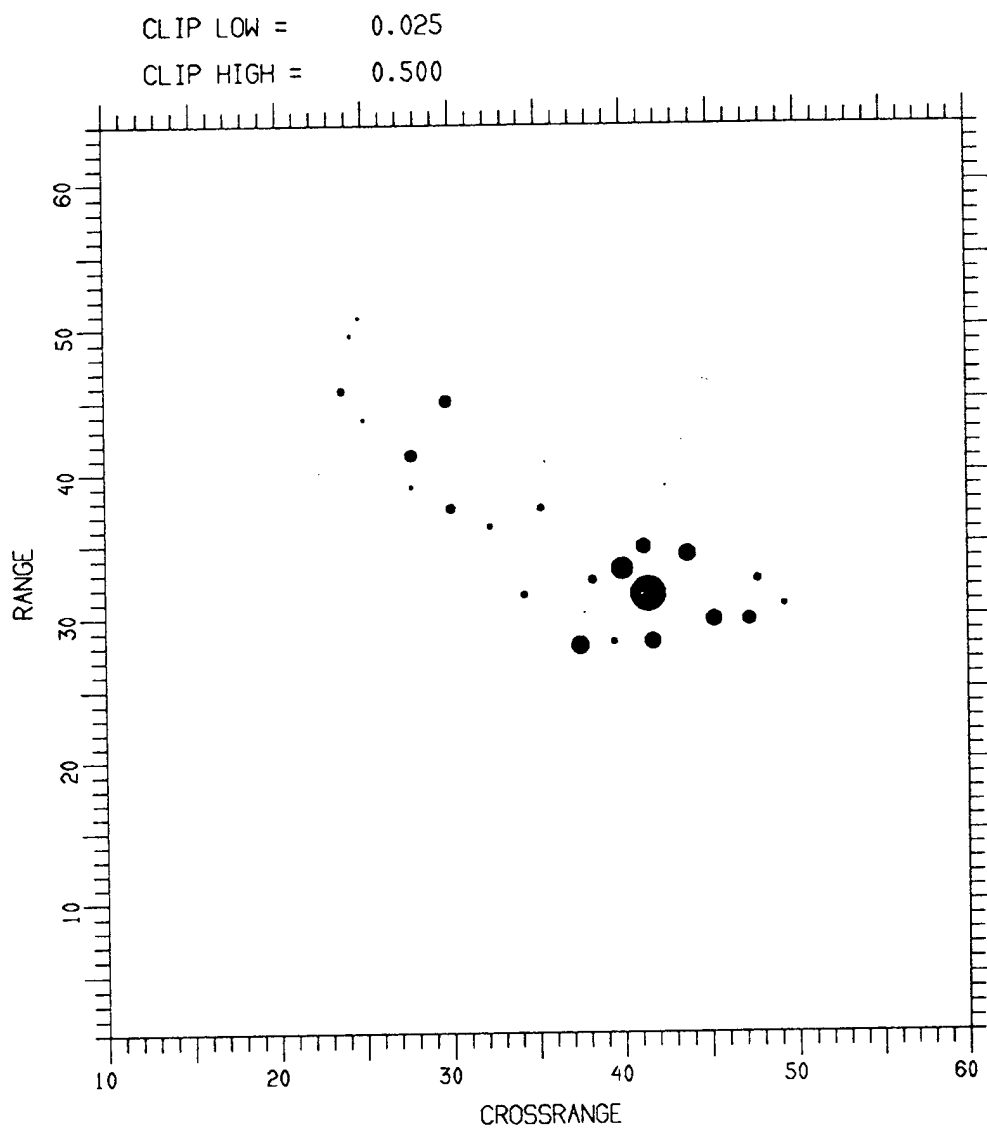


Figure 3.14. Third Vehicle Image.

measured positions with the predicted positions for the vehicles of interest. In actual fact, the measured position of a peak need not represent the position of a scatterer, so that the nature of each peak must be analyzed before positional measurements are derived. This analysis must use the complex image rather than the intensity image [1].

In analyzing a given peak observed in the intensity image, we must decide between the following possibilities: (1) the position of the peak represents the position of a scatterer on the vehicle; (2) the position of a peak is determined by interference between scatterers, so that the positions of these scatterers must be derived; (3) the peak represents a response that is smeared through the phase center motion of the associated scatterer; and (4) the peak represents a spurious response from a scatterer that can be far removed. At this time we do not have a good way of utilizing spurious responses for target identification, so that the task is to recognize and disregard the spurious responses and, to the extent possible, detect genuine responses partially masked by spurious responses. We will summarize the results of our image analysis, with the details of how the actual measurements are performed given in [1].

Briefly, for a given response peak we take ten image cuts through the peak, with the image cuts spaced at regular angular intervals so as to cover 360° in the image plane. If in all ten image cuts the amplitude of the transform of the response has no deep breaks and the phase function no rapid jumps, we take the position of the peak as the position of a scatterer. If in all ten image cuts we observe the amplitude and phase patterns characteristic of the interference between two fixed scatterers, we assume two scatterers and calculate their positions based on this model. If in some of the ten image cuts the amplitude and phase pattern of the transform degrades so much from that expected from two fixed scatterers (primarily by having strongly curved phase functions) that the model of two scatterers cannot be applied, we conclude that the response is due to a scatterer with mild phase center motion, and accept the peak position as the position of the scatterer. If the phase function of the peak is strongly curved, with the curvature varying over the ten image cuts and disappearing in one or two directions in the image, we assume that the response is a spurious sideband response. It will then be one of a set of often poorly resolved responses for which the lines along one of

the directions with linear phase all intersect in one point, which is taken as the position of the scatterer responsible for the set of spurious responses.

Our matching task is made more difficult by the fact that, as is often the case with real data, we have only imperfect ground truth. The vehicle is equipped to carry various corner reflectors and antennas on its roof, and the positions of this equipment are variable and unknown for our data. Thus we must concentrate on the equipment and features associated with the original manufacture of the vehicle. Since the vehicle was moving on a wide paved surface, so that ground bounces may be important, we should also have information about the features on the underside. Despite these difficulties, however, the example should be illustrative.

The occurrence of spurious sideband responses depends on the design complexity of the vehicle and its motion behavior. Recreational vehicles have generally smooth shapes, but the vehicle is turning rather than proceeding along a straight path. Spurious responses thus may or may not be a problem. The analysis showed that many of the strong responses in the lower part of the image of Figure 3.12 are spurious. The cause could be the feature formed by the combination of the spare wheel with the backside and the corner formed by the rear bumper. The other possibility is a complicated feature underneath the vehicle, illuminated via ground bounce. For our purposes the important point is that we want to ignore these spurious responses regardless of their origin, and want to try to detect genuine responses from the back of the vehicle.

For the image of Figure 3.12, the template match of the three-dimensional distribution of the features on the vehicle with the range/crossrange positions of the accepted responses is shown in Figure 3.15, with the crosses marking the measured response positions and the letters the feature positions. The scale of Figure 3.15 is ten times that of Figure 3.12. For most features the match is a good one, so that we will discuss only the special cases.

The position of the left front corner of the vehicle is marked by a question mark in Figure 3.15. This corner is not visible, because for this aspect angle the start of the bumper is shaped like a bent waveguide. Thus we obtain the delayed response visible in the same crossrange gate, which is only the first in a series of unresolved delayed responses of decreasing magnitude, not shown in Figure 3.15. Features K and L are the backs of air conditioning

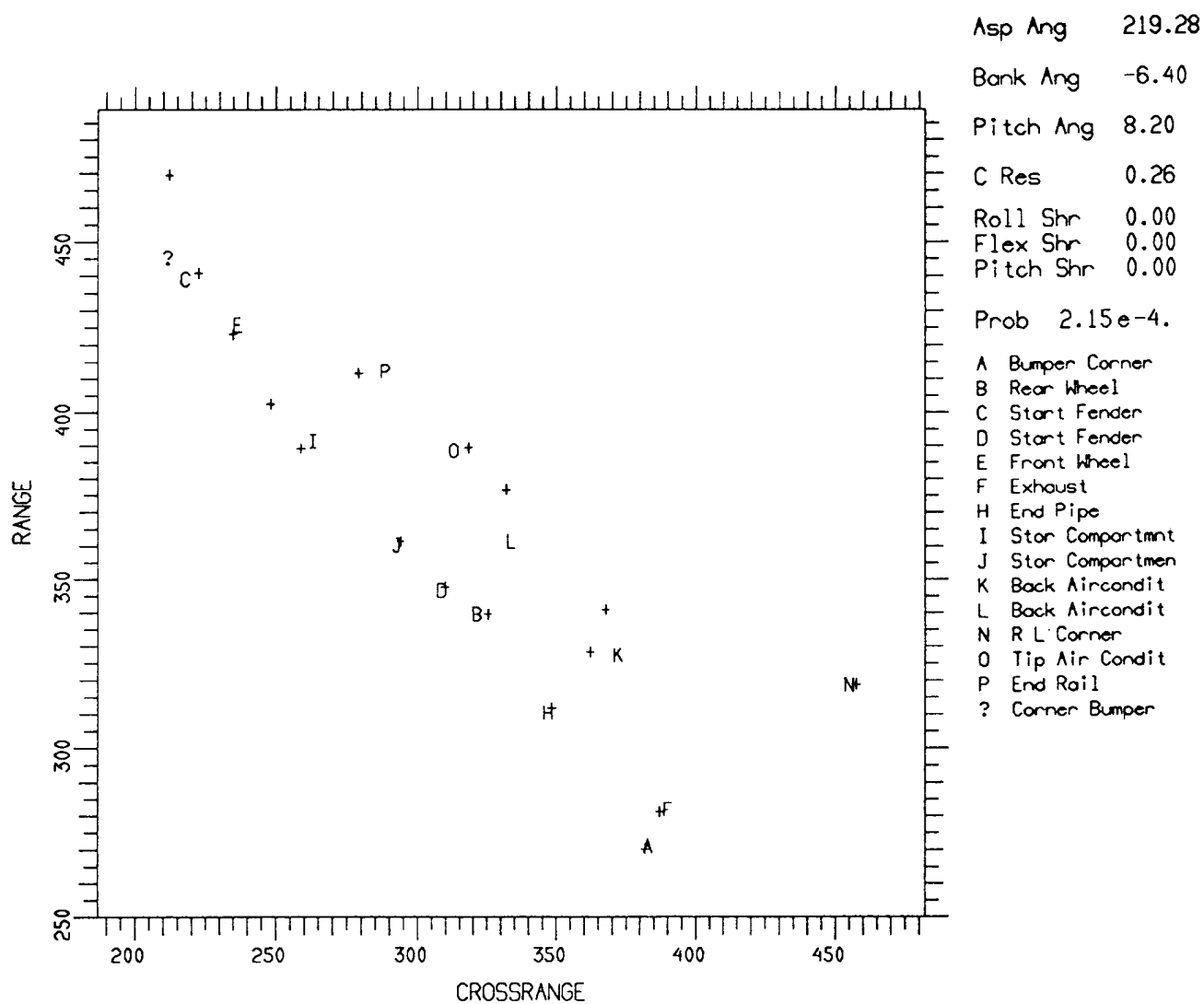


Figure 3.15. Positional Match for the First Image.

units, which at this aspect angle (51° off broadside) cannot be readily detected. However, the wave penetrates into the units, so that delayed responses are observed. For one of the readily observable responses we do not have a matching feature. The feature is likely to be on the underside of the vehicle, where it can be observed via a ground bounce.

A close examination of Figure 3.15 indicates that it is unlikely that another vehicle might match the measured distribution of the features. Hence, even though one can and will augment the positional match with measured characteristics of some vehicle features, in this case the positional match alone should be sufficient for vehicle identification. Note that the match implicitly provides the length. If we had better information on the devices on top of the vehicle, or if there were not so many strong spurious responses at the back of the vehicle, the match would also confirm the width of the vehicle. We also note that in this instance the SAR image allows extracting so much of the vehicle path that aspect angle and aspect angle changes can be measured accurately enough to establish the crossrange scale factor of the image independently. The good quality of the match of Figure 3.15 indicates that either the flexing effects are insignificant or the imaging time was indeed well selected. We will see below which of the two factors is responsible.

For the second image, presumably also formed at a good time, the positional match is shown in Figure 3.16. As seen from the printout, the aspect angle is smaller by about 9° , so that the vehicle is viewed 60° off broadside. There are several differences between the matches, even though the aspect angle change is only 9° . However, by far most of the measured responses persist from one image to the other.

Whereas the differences above are minor, the situation is much worse for the image at the intermediate time, for which the positional match is shown in Figure 3.17. First, because of the relatively poor match for the features on the side of the vehicle, the measured aspect angle is in error. It should be between the angles for Figures 3.15 and 3.16. Although some of the feature positions are almost perfectly matched, for a significant number the match is poor. Moreover, there are a number of features for which there are no significant responses (higher than the background), and there are responses for which we cannot find a feature on the vehicle. These large differences

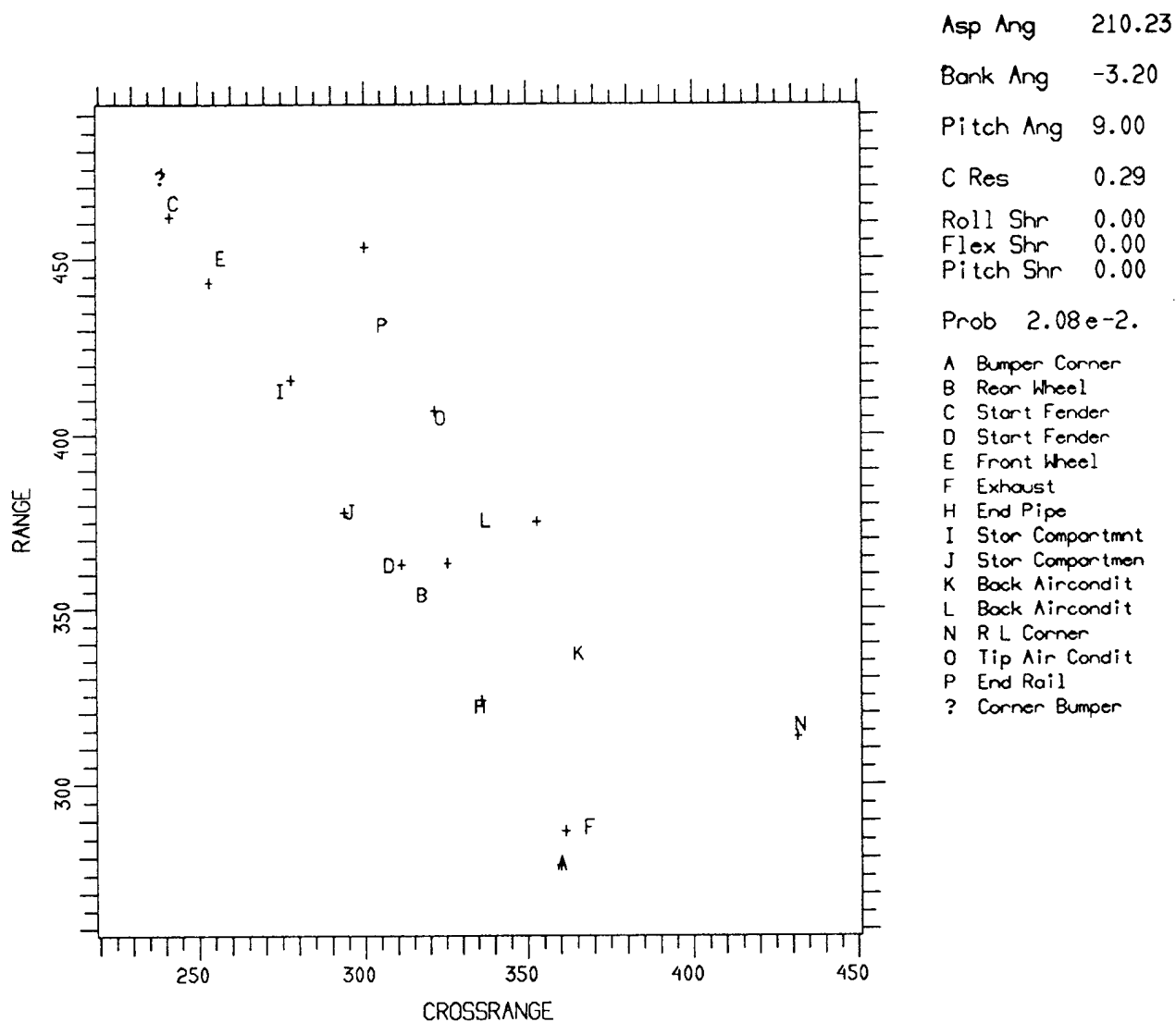
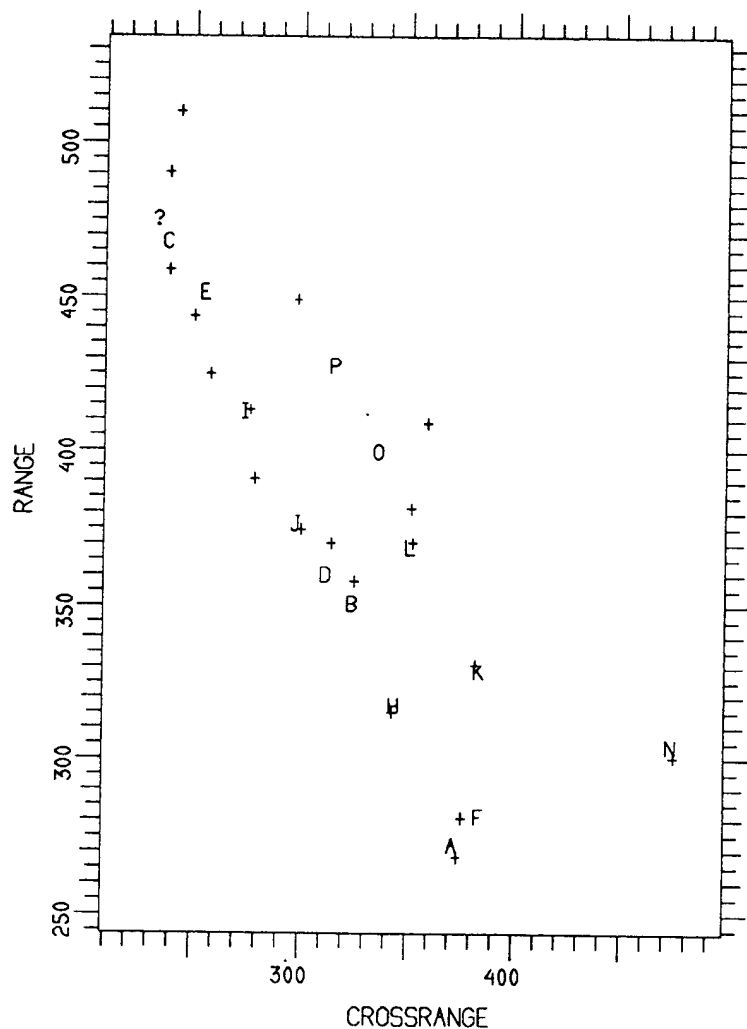


Figure 3.16. Positional Match for the Second Image.



Asp Ang 205.26

Bank Ang -4.60

Pitch Ang 9.30

C Res 0.22

Roll Shr 0.00

Flex Shr 0.00

Pitch Shr 0.00

Prob 4.49e-8.

- A Bumper Corner
- B Rear Wheel
- C Start Fender
- D Start Fender
- E Front Wheel
- F Exhaust
- H End Pipe
- I Stor Compartmt
- J Stor Compartmen
- K Back Aircondit
- L Back Aircondit
- N R L Corner
- O Tip Air Condit
- P End Rail
- ? Corner Bumper

Figure 3.17. Positional Match for the Third Image.

exist despite the fact that the imaging time falls between the times for Figures 3.15 and 3.16, which both show good results. The difficulties must be ascribed to the poor choice of the imaging time when bending/flexing effects are significant. Note, however, that the significantly poorer results do not necessarily imply that identification is impossible. A good number of responses are still well matched, and identification need not depend solely on the positional match.

3.6 THE SPECIAL CASE OF IDENTIFICATION AT BROADSIDE ASPECT

3.6.1 The Broadside Problem

Target identification by means of radar is a difficult problem, and it is most difficult when the target is viewed at broadside. These difficulties are greatest in the important case of a moving ground vehicle in a SAR scene when viewed at broadside. Then clutter cancellation via DPCA processing is only partly successful, because for the broadside aspect the range rate of the vehicle is near zero, so that the vehicle returns get cancelled together with the clutter. At the broadside aspect the visible scatterers tend to be concentrated at the illuminated edge, so that range resolution is not very helpful. However, it is difficult to perform the motion compensation when resolution is mainly in crossrange, which is the type of resolution that requires a good motion compensation. Many targets also tend to generate specular flashes at broadside aspects, with their effective points of origin sometimes shifting in crossrange. It is problematic to utilize such flashes for target identification, and yet because of their strength and smearing they hide important scatterers that could be used.

For the Winnebago RV we now will demonstrate that the problems can be overcome and that target identification at broadside is indeed feasible. Again, the underlying thinking is that it is not sufficient to generate some kind of "focused" ISAR image that is to display the shape of the target and its substructures, but that it is necessary to generate an ISAR image in which the *individual responses* are focused. Only then can one perform the measurements that allow determining the locations of the scatterers associated with the individual responses. In good cases one can also analyze individual responses to extract characteristics of the scatterers. In the following we again address the problem of the positional measurements on target scatterers.

The flat sides of the Winnebago RV cause particular problems at the broadside aspect. On the plus side, the vehicle is turning on a paved surface.

3.6.2 Motion Compensation

Reference 1 describes a general motion compensation for targets whose motion is not perfectly smooth, which is more often than not the case in practice. This motion compensation uses range centroid tracking on the entire target, followed by Doppler centroid tracking on the entire target. The next steps involve measurements and tracking of individual scatterers rather than the target as a whole, with the first step following the centroid tracking consisting of the Doppler tracking of a suitable scatterer.

A succession of range profiles of the data before clutter cancellation is shown in Figure 3.18. Around the time of 13.1 s the signal strength increases significantly, implying that the target goes through the broadside aspect. Range profiles over the same time interval but after clutter cancellation are shown in Figure 3.19. Figure 3.19 shows less amplitude variability with time, indicating that clutter cancellation is also beneficial for suppressing the specular flash. Thus we will use the data after clutter cancellation.

Since dwell time of the SAR system is designed to provide high crossrange resolution on stationary targets, a much shorter time interval is adequate for imaging the moving vehicle. In fact, the SAR imaging time allows determining the vehicle motion, showing that the vehicle is turning roughly at 15° per second. If we choose an imaging time of 0.3 s, for example, the vehicle will turn by about 5° over the imaging time. At a wavelength of 2 cm we obtain a crossrange resolution in the order of half a foot. Thus we select an imaging time from 13 to 13.3 s, which includes the broadside aspect.

When the range centroid track is followed by a Doppler centroid track, we obtain the image of Figure 3.20. The image is in peaks plot form, where every dot indicates a local maximum of the intensity image. The diameter of the dot is proportional to the amplitude of the maximum. Only the responses exceeding -20 dB relative to the highest peak of the image are shown, since otherwise the plot would include too much clutter. The next desired motion compensation step would be the Doppler tracking of a selected response. However, the responses are insufficiently resolved, as is seen from the image cut in the range gate containing the strong responses as given by Figure 3.21. To

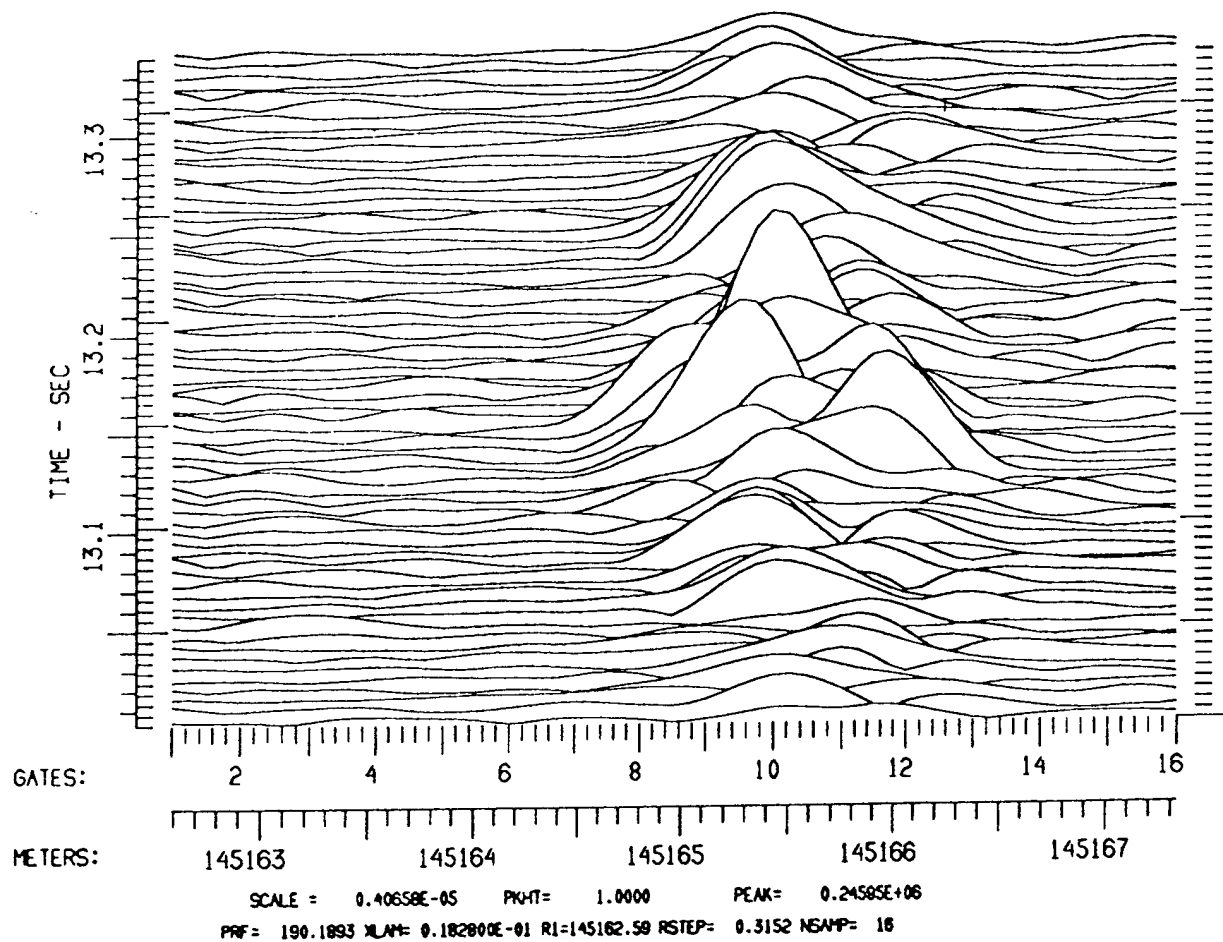


Figure 3.18. Range Profiles Before Clutter Cancellation.

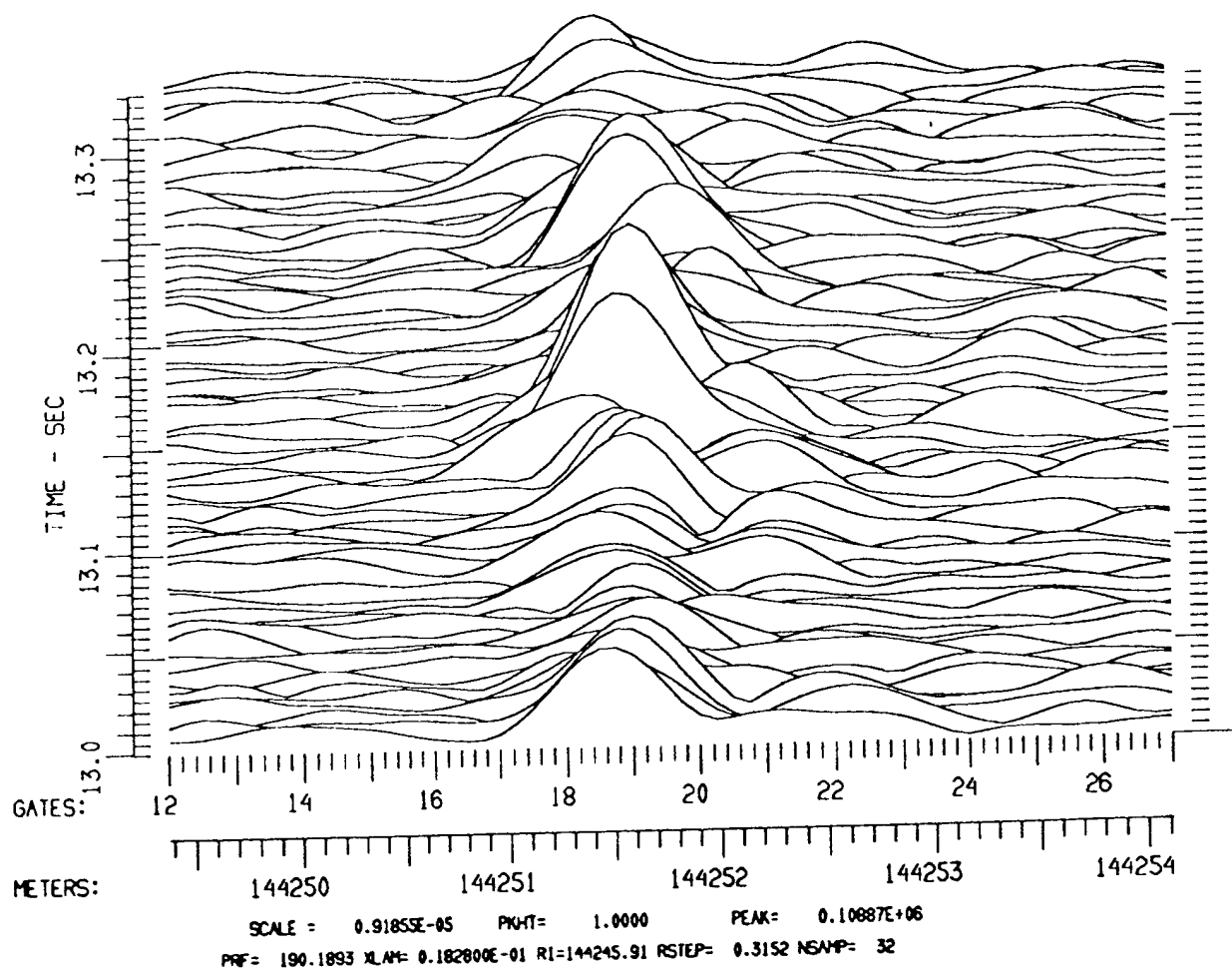


Figure 3.19. Range Profiles After Clutter Cancellation.

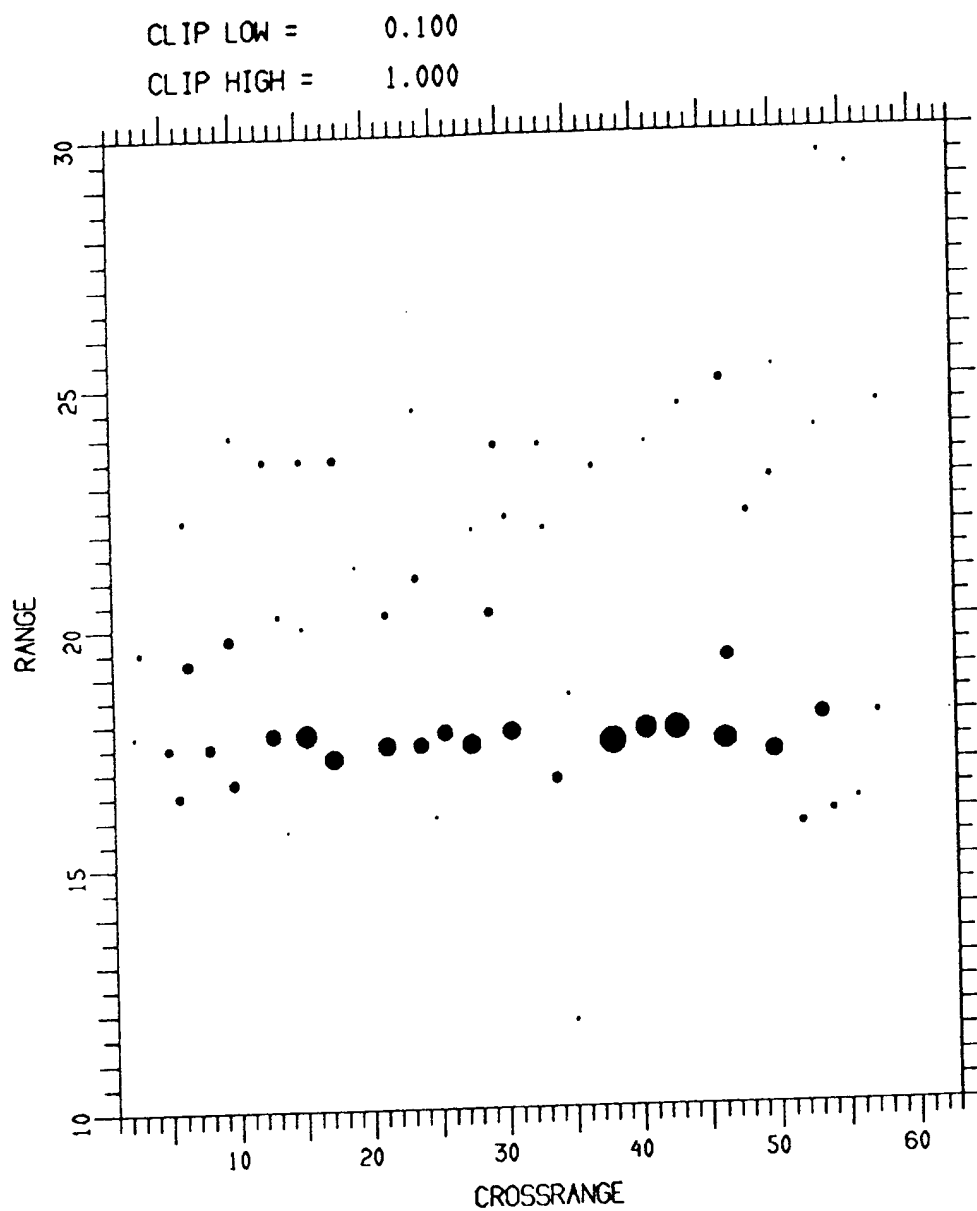


Figure 3.20. Image After Range Centroid and Doppler Centroid Track.

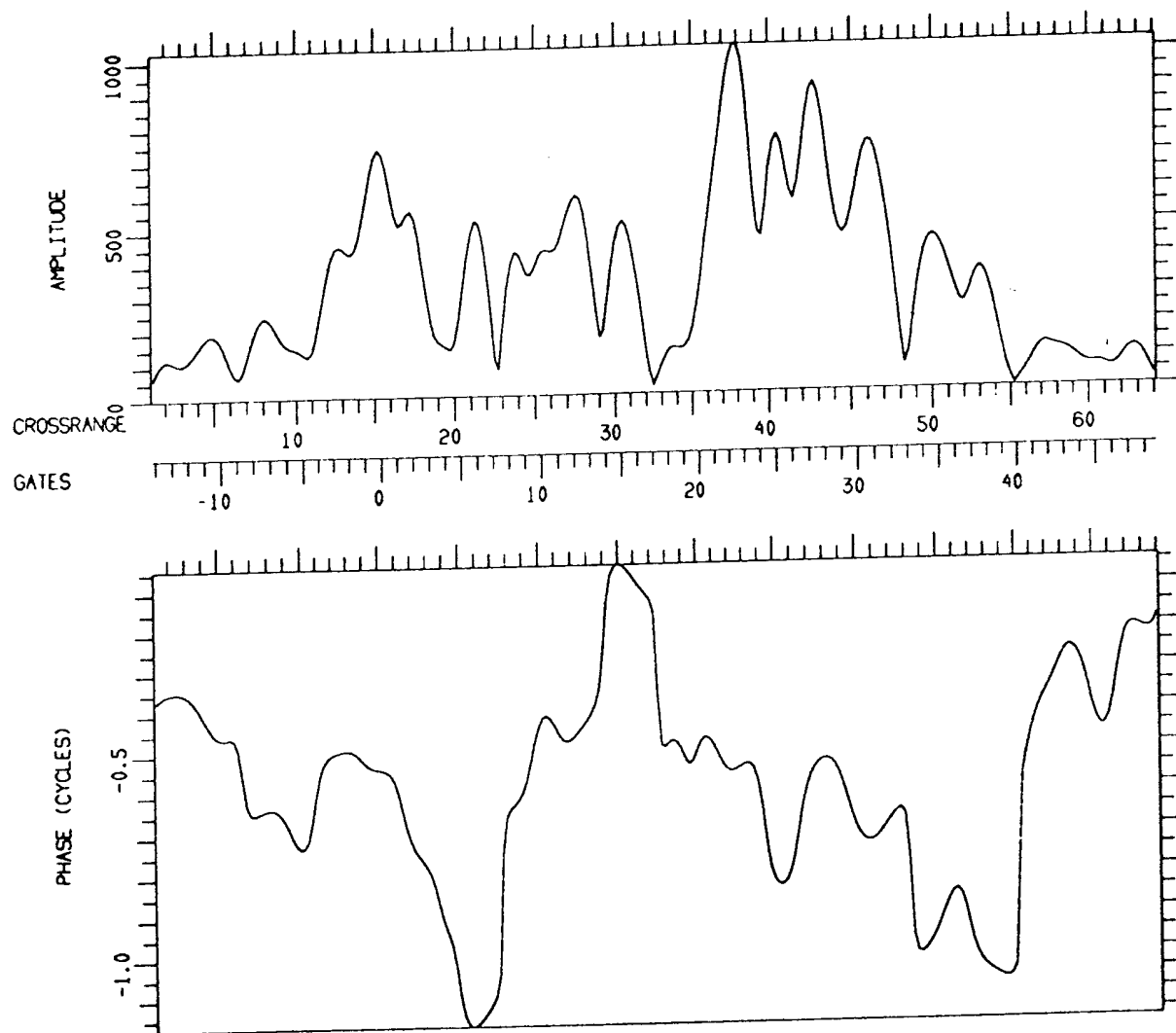


Figure 3.21. Image Cut in Range Gate 17.7.

perform Doppler tracking of a scatterer, we would have to form sub-images with reduced imaging times, which would further degrade crossrange resolution. Thus we find from the data that under the present circumstances we must work with the image of Figure 3.20.

3.6.3 Interpretation of the Image

First, we must decide whether the image is usable for positional measurements on the scatterers. Are the strong responses in about Range Gate 17.7 meaningful in that they allow measuring the positions of the associated scatterers, or do they represent a meaningless speckle pattern? For a test we must take the Fourier transforms of the complex peaks. If the transform of a peak gives the amplitude/phase pattern generated by a single or by multiple interfering scatterers, the image is usable for positional measurements. If the transforms of the peaks show that at most two scatterers are interfering, we can perform the measurements [1]. If more than two scatterers are interfering, we must improve crossrange resolution by increasing the imaging time.

As an example, in Figure 3.22 we show the transform of the (complex) peak in Gate 38 of Figure 3.21. The amplitude/phase pattern is a good approximation of the ideal pattern from two interfering scatterers [1], and the two scatterer positions in crossrange are printed at the bottom of the figure. Similar measurements can be performed on all the major responses of the image, giving the positions of either single scatterers or pairs of scatterers. With respect to the weaker responses, on the other hand, there does not appear to be a general and reliable method of distinguishing between a target response and a clutter response. Most of the weaker responses must be dismissed because they do not sufficiently exceed the clutter background. However, even for the weaker responses we should look for response patterns that can be generated only by man-made targets.

For an illustration, consider the image cut in Range Gate 23.4, as shown in Figure 3.23. If we examine the image cuts in the crossrange gates of the peaks within the marked window, we find that all have peaks in almost exactly in the same range gate. This would not be expected of clutter. Furthermore, taking the transform of the complex response within the indicated window gives the time function of Figure 3.24. Despite the rather high background, it is

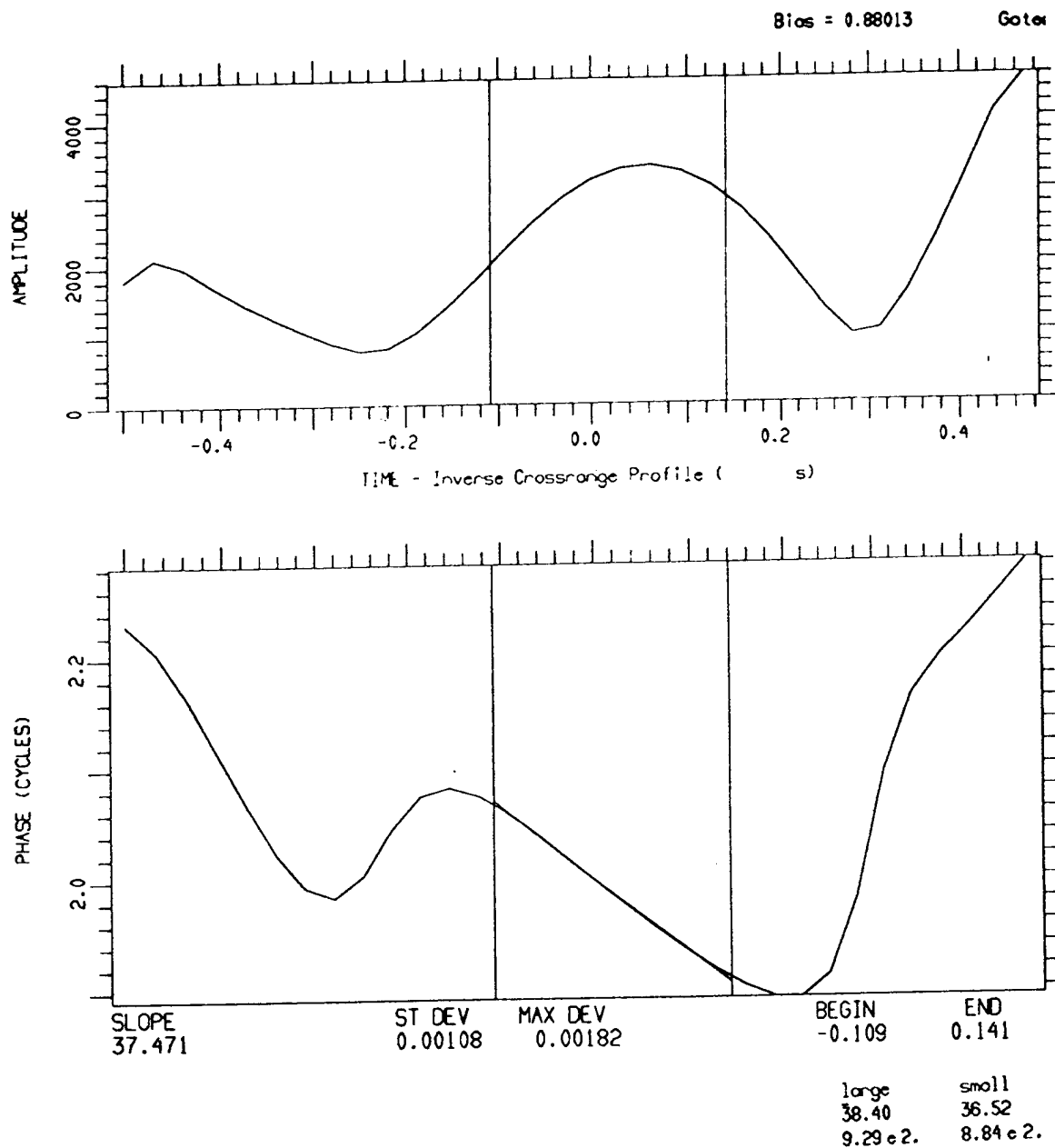


Figure 3.22. Transform of the Peak in Gate 38 of Figure 3.21.

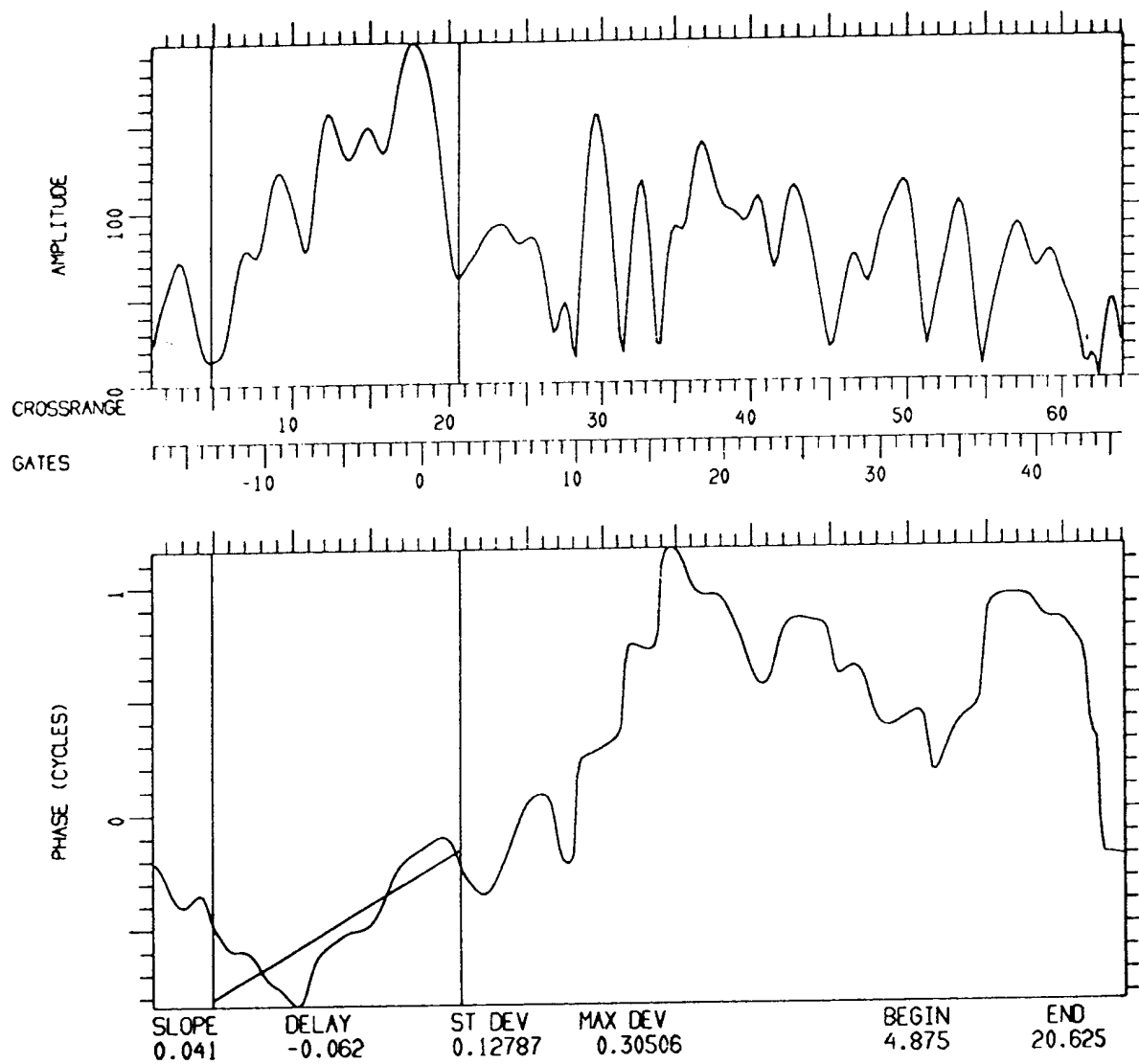


Figure 3.23. Image Cut in Range Gate 23.4.

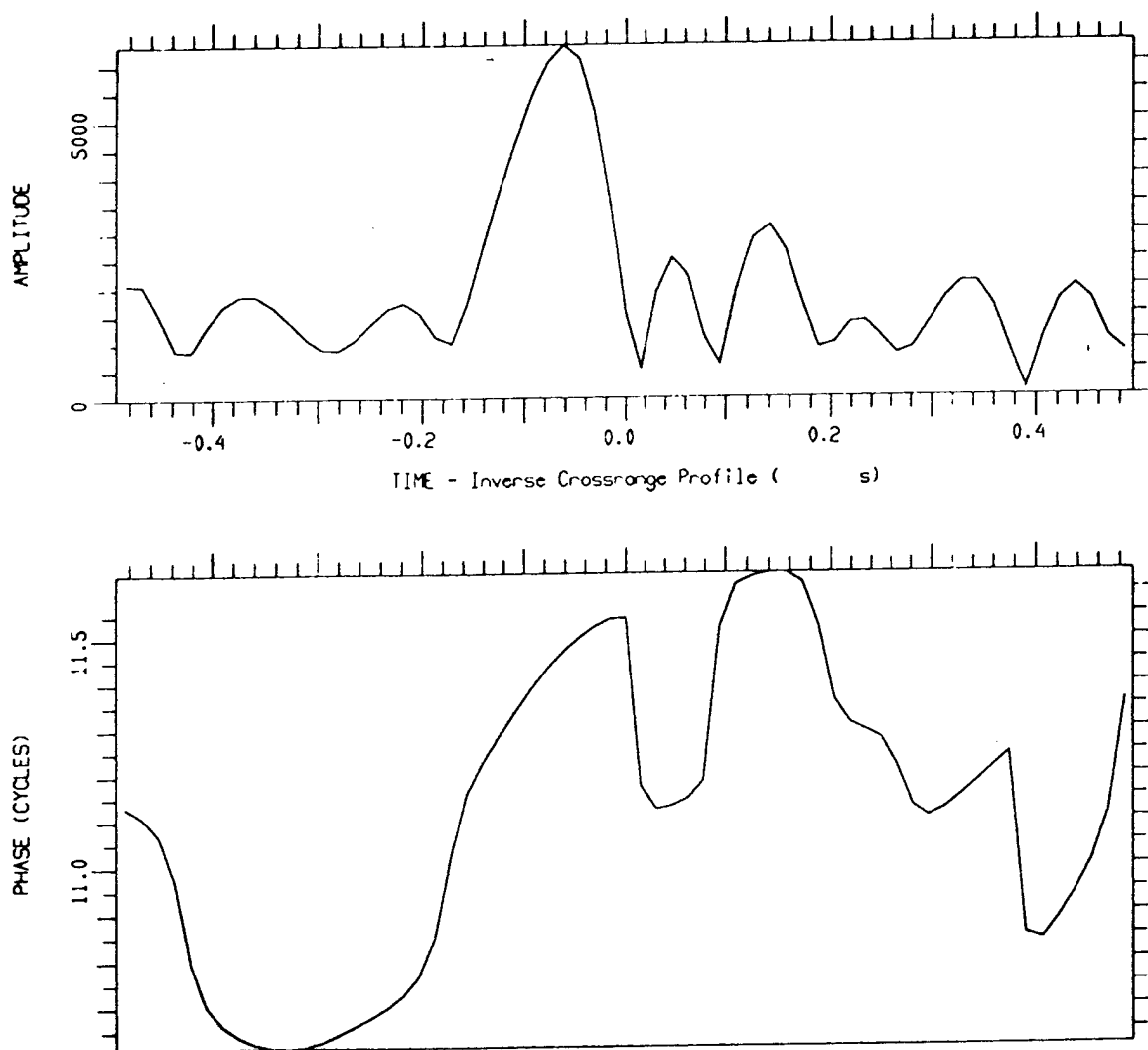


Figure 3.24. Transform of the Responses Within the Window in Figure 3.23.

unmistakable that there is a specular flash. Thus we conclude that we are observing a vehicle scatterer. Moreover, many of the stronger responses outside the marked interval in Figure 3.23 also are at the same range. The implication is that we have found part of the far edge of the vehicle.

3.6.4 Scatterer Prediction

To make use of the measured scatterers in the process of vehicle identification, we must correlate the measured positions with the predicted scatterer positions of the vehicles of interest. This correlation is performed via a template match [3]. Although the observable scatterers will change with aspect angle, the change is slow. A photograph of the vehicle is shown in Figure 3.25. The features on the top of the vehicle can be rearranged or taken off at any time, and we do not know the condition of the vehicle at the time of the radar observation. Hence, only the air conditioners are reliable. With respect to the scatterers of the near edge, we simply measured the locations of all features and discontinuities that should give rise to observable backscattering. This means the side of the front bumper, the four "corners" of the fenders, the wheels, the beginnings and ends of the compartments, and so forth. The resulting template match with the measured scatterer positions is shown in Figure 3.26, on a scale ten times that of Figure 3.20.

Considering the problems of clutter and backscattering at the broadside aspect, the match for the scatterers on the near edge is surprisingly good. The measurement with the mild specular flash also gives a good match with the upper right front corner of the vehicle, represented by N. We have not indicated the other measurements that fall along the far edge, in the range gate of N. As already remarked, the features on the top of the vehicle are less reliable, and they also give weaker responses at the broadside aspect.

In conclusion, target identification becomes more difficult as the aspect angle increases, and is most difficult at broadside aspects. However, as we have demonstrated, the problems are solvable provided that we utilize the complex image rather than the intensity image. Automation of the various tests and measurements is not trivial but can be done. Perhaps the biggest

challenge is to predict which scatterers will be visible on different vehicles. In that respect we have taken a simple approach here and were correct.

3.7 SUMMARY

In our experience the positional match for target features is a necessary input to target identification. We have shown that the match can be derived on the basis of the same general principles, using complex-image analysis, regardless of whether the target is an aircraft or a moving ground vehicle. Roughly speaking, as far as the degree of difficulty of target identification is concerned, smoothly flying aircraft are comparable to stationary ground vehicles, and maneuvering aircraft to moving ground vehicles. There is more variety in ground vehicles, however, because the differences in their designs and motion behavior are far larger than for aircraft. This makes ground vehicle identification under all circumstances more difficult than aircraft identification.



Figure 3.25. The Winnebago Recreational Vehicle.

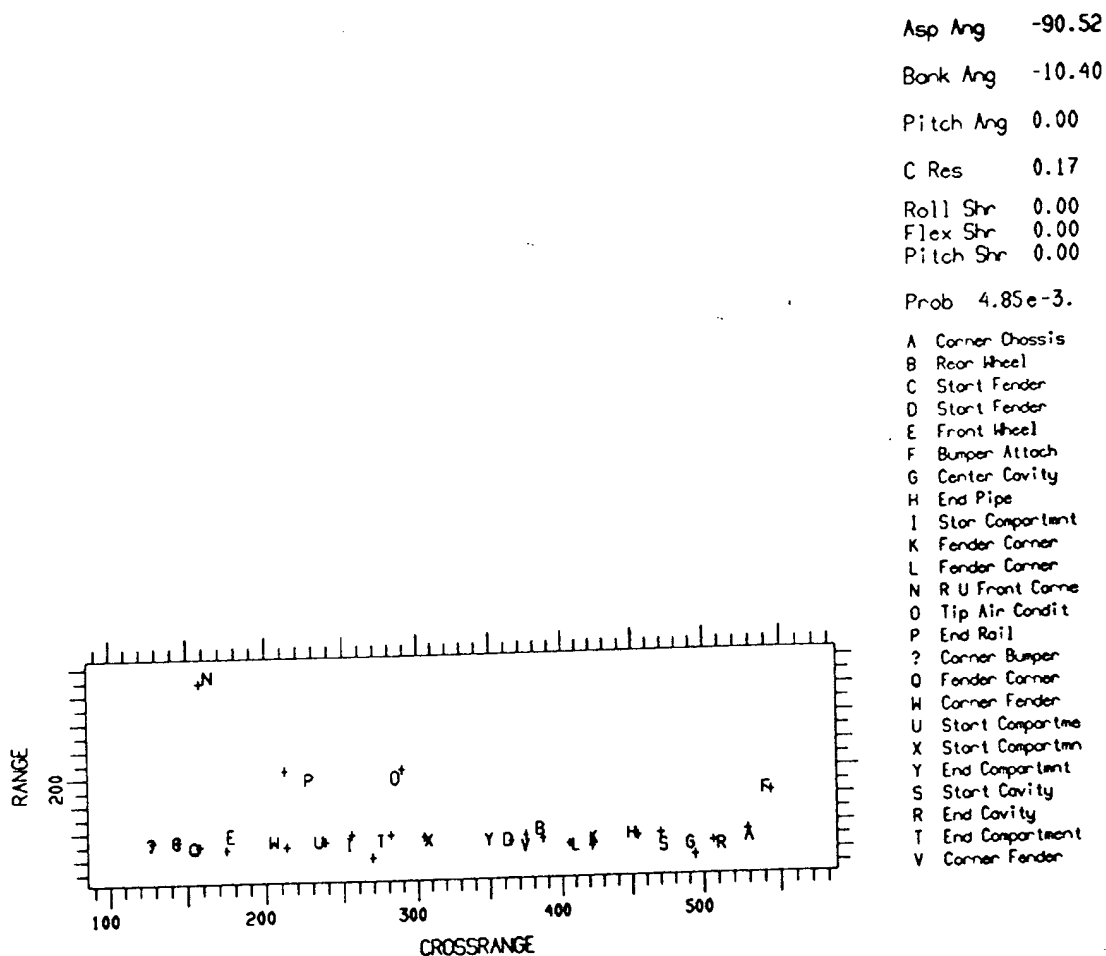


Figure 3.26. Positional Match Between Measured and Predicted Scatterers.

4. THE ADAPTIVITY REQUIREMENT FOR ISAR IMAGING

4.1 ADAPTIVE AND NONADAPTIVE ALGORITHMS

Simple, nonadaptive algorithms are available for the detection of a target in noise, target detection in clutter, for the tracking of a target, for clutter cancellation, and for similar radar tasks. Can we have such an algorithm, or possibly more than one algorithm, for target identification? In this section we demonstrate that the answer is no. The variety of targets is so large, in particular for ground vehicles, and the vehicles can behave in so many different ways that only a highly adaptive algorithm can accommodate all the different conditions. We must have available a set of processing procedures, and in a given application adaptively choose the particular subset that leads to an image good enough for identification of the target. We will now show how this is done for a vehicle moving slowly along a paved road. It is a relatively benign case, and yet adaptivity will be seen to be essential.

We again emphasize that all of our treatment is based on the premise that radar identification of a target requires more than the formation of some "focused" image that may, or in many cases may not, have the general shape of the target. Such an approach may be good when we use an optical system with high resolution in azimuth and elevation, but not when the sensor is a radar with range and Doppler resolution. Here the situation is radically different from that at optics, both because of the much more complicated backscattering behavior of the target at radar frequencies and the difference between resolution in two angles and resolution in range and Doppler. In our experience it is necessary to generate an ISAR image in which the individual responses are focused. In fact, focusing of the responses is not enough, because it implies working with the intensity image; yet in radar applications we must utilize the complex image. Only then can one accurately measure the locations of the scatterers, and in some cases also determine the scatterer characteristics. We will describe the processing needed to form such an image, as well as the tests performed to determine the next step in the sequence of processing steps. Although only certain measurements will be used, which of them are needed and how they are utilized will be highly specific to the selected example. This fact further illustrates the necessity of adapting the entire process to the case on hand.

4.2 DETERMINING THE VEHICLE MOTION BEHAVIOR

The vehicle of our first example is a refueling truck for aircraft, and it is moving on a paved road. The motion thus is relatively smooth. Moreover, the speed of the vehicle is only about 15 miles per hour, which makes its motion even smoother. On the other hand, the radar is viewing the vehicle close to tail-on and the vehicle is moving along a line, so that a long dwell time is needed if a useful degree of Doppler resolution is to be achieved. If the vehicle should have even small bouncing or yawing motions, they will have to be taken into account in imaging. Under these travel conditions any yaw motion is unlikely to be large enough to facilitate crossrange resolution, but it may be large enough to corrupt the image if not taken into account. All of this must be determined before selecting an imaging interval and deciding how to motion compensate. We will start with an imaging time of 2.7 s, which in this instance is a good fraction of the available dwell time. Extending the imaging time by perhaps a factor of two will not change the situation significantly.

The objective is to form a (complex) image of the vehicle, and extract sufficient information from the image to identify the vehicle. The foremost problem thus is the motion compensation needed for generating the ISAR image. The conditions under which a ground vehicle is imaged can change so drastically for the same target, and even more so from one target to the next, that there can be no "standard" motion compensation. In [1] we describe a multi-step motion compensation for aircraft. Different aircraft are much more similar in appearance than different ground vehicles, and the motion behavior of aircraft also is much more limited in its characteristics than that of ground vehicles, since the latter can go on good roads, poor roads, off roads, and at grossly different speeds. They also have different weights, constructions, and suspensions. Nevertheless, even the motion compensation for aircraft cannot be viewed as one motion compensation algorithm. Rather, we must adaptively select the various motion compensation steps as demanded by the situation. This is much more so the case for ground vehicles. We must adopt the view that we have available a set of motion compensation steps, and that the type and sequence of these steps must be adapted to the situation on hand. Hence, when we subsequently go through various tests and decisions, they are not meant merely for illustration. These are the tests and decisions

that also must be implemented in fully automated fashion in an operational identification system.

Before we can proceed past the crudest motion compensation steps, we must measure the motion behavior of the vehicle. In order not to camouflage the motion behavior by undesired but unavoidable consequences of motion compensation steps, for the analysis of the vehicle motion we can use only the first crude motion compensation steps for the vehicle as a whole, never the motion compensation steps on individual scatterers. Since there is no important difference between different ways of compensating the vehicle as a whole, we shall use the range centroid tracking followed by Doppler centroid tracking as described in [1]. Under some circumstances it may be desirable to modify these steps, but the important requirement is that in these first two steps we must not fit splines that are so flexible that they could introduce false motion components. We use polynomial fits of an order no higher than quadratic.

The image of the vehicle after range centroid and Doppler centroid compensation is shown in Figure 4.1, in the so-called peaks plot format rather than the conventional form of an ISAR image. In this plot each local maximum of the intensity image is represented by a dot whose diameter is proportional to the amplitude of the maximum. The image may appear to be that of a rectangular vehicle, but this impression is caused by the fact that due to the poor motion compensation the responses are smeared in crossrange. We next analyze the motion behavior of the vehicle to determine whether it acts as a rigid vehicle, in which case the motion compensation is much simpler than when bending is important. If the vehicle acted as rigid for radar purposes, compensation could be based on the motion of just two responses. With nonrigid ground vehicles we must analyze responses in different positions within the image to determine how different parts of the vehicle behave.

We consider the strongest response, the one in Range Gate 32.9. The image cut in this range gate is shown in Figure 4.2. The next step is to test whether the response function is generated by a single scatterer, with smearing in crossrange due to poor motion compensation, or whether these are responses from several scatterers. In the first case the transform amplitude will not have deep minima and the phase function will lack sharp jumps, whereas in the second case we will observe a strongly fluctuating amplitude

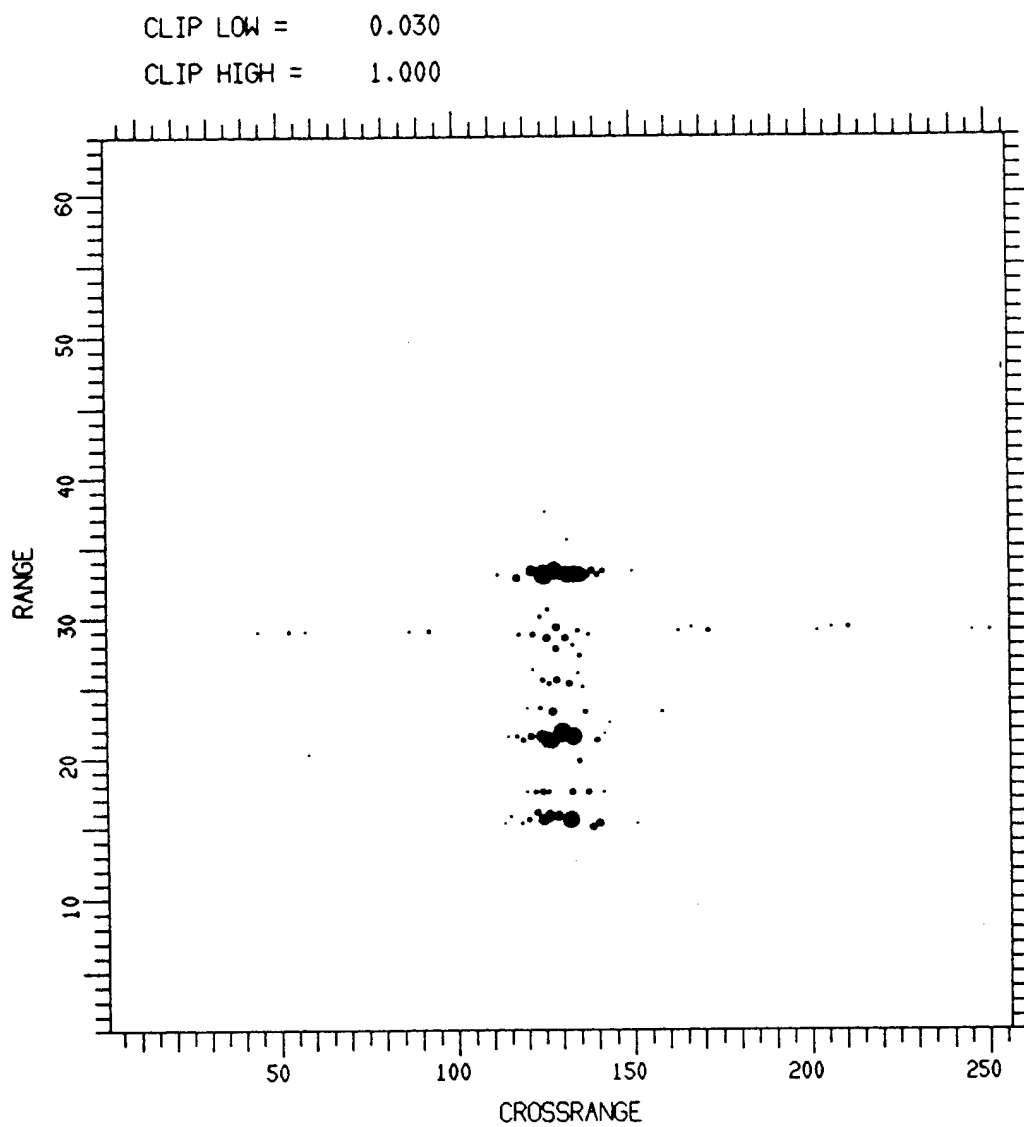


Figure 4.1. Peaks Plot Image of the Vehicle After Range and Doppler Centroid Compensation.

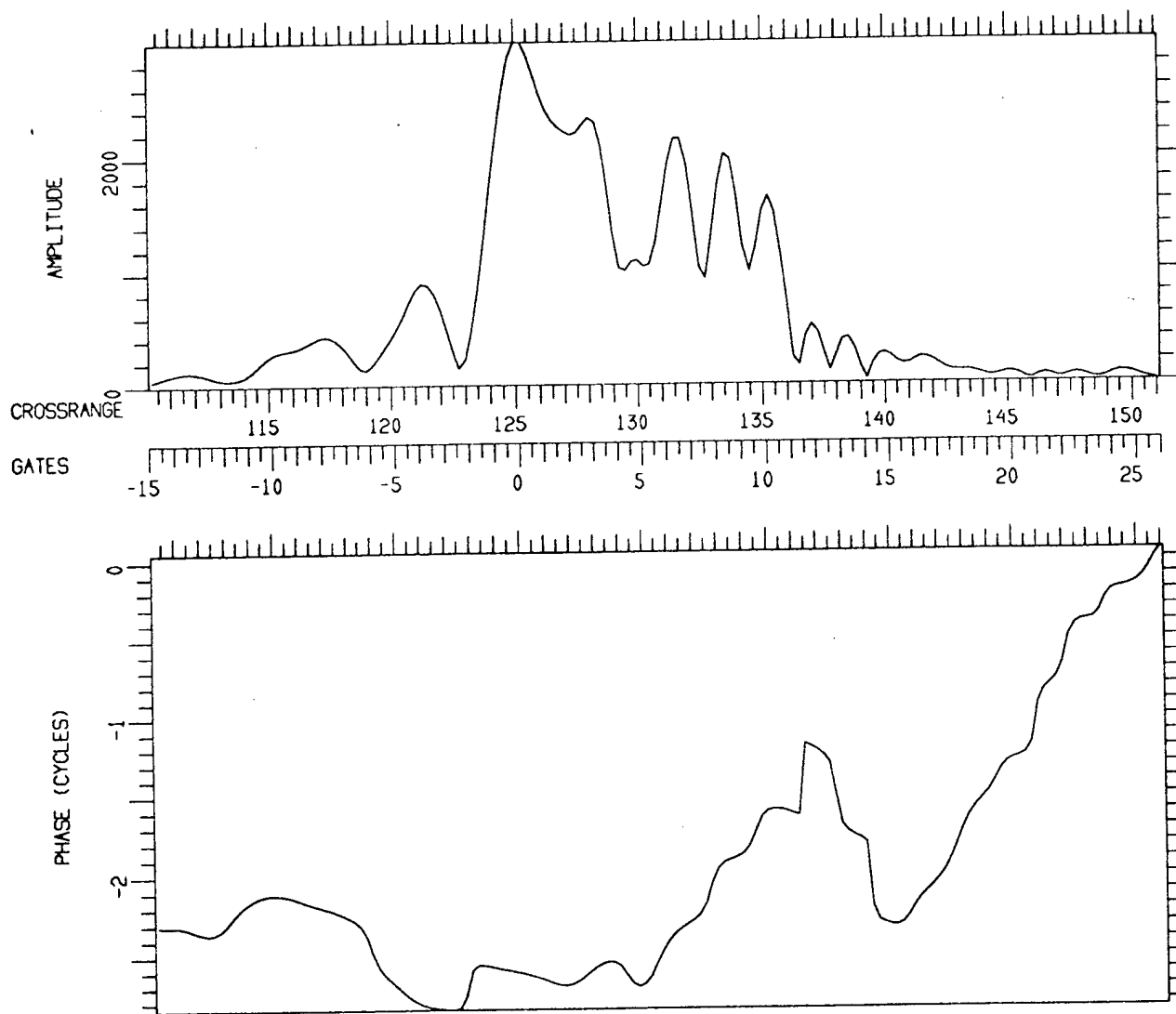


Figure 4.2. Image Cut in Range Gate 32.9.

with large phase jumps [1]. If the transform shows a nearly constant amplitude, the phase function will describe the motion behavior of the scatterer. If the amplitude is strongly fluctuating, we must process in a way so that the fluctuations disappear.

The transform of the image cut is shown in Figure 4.3. The amplitude function does show significant breaks, but not deep enough to destroy the dominance of a single scatterer. The amplitude minima are almost regularly spaced, which signifies that the interference comes mainly from a second scatterer. On the basis of resolution theory, at each amplitude minimum the second scatterer introduces a phase jump, with the magnitude of the phase jump increasing with the depth of the amplitude minimum. The phase jump attains the largest value of 0.5 cycles when the amplitude minimum has zero value. With the heights of the minima as seen in Figure 4.3, the phase jumps are in the order of 0.2 cycles. If we mentally remove these phase jumps, we find that the shape of the phase function is not strongly changed by the phase jumps. The conclusion thus is that the phase slope roughly switches between four different values. Since phase slope is Doppler or crossrange, the response of the major scatterer will appear in four parts, each part centered in one of the four crossrange gates determined by the phase slope. A measurement of the phase slope values gives, from left to right, Crossrange Gates 129.1, 133.8, 125.1, and 135.8. It is seen from Figure 4.2 that these crossrange gates cover the main part of the smeared response of Figure 4.2.

Having determined the behavior of the dominant scatterer in Range Gate 32.9, we must check scatterers in other range gates. If the behaviors are all the same or they are smoothly changing with the separation from the dominant scatterer, the vehicle is moving as a rigid body. If they are different, we must individually compensate the scatterers. We take image cuts as in Figure 4.2 in the range gates of the other strong scatterers, Gates 15.4 and 21.6. The transforms have very similar characteristics as in Figure 4.3. In Figure 4.4 we show the phase functions of the transforms of the image cuts in the three range gates of the major scatterers. For our crude comparison we must ignore at least the major phase jumps, the one near the center of the middle plot and the three at the left side of the bottom plot. We then find that the bottom two phase functions are nearly alike, except for a displacement of the minima of the phase functions. On the other hand, the phase

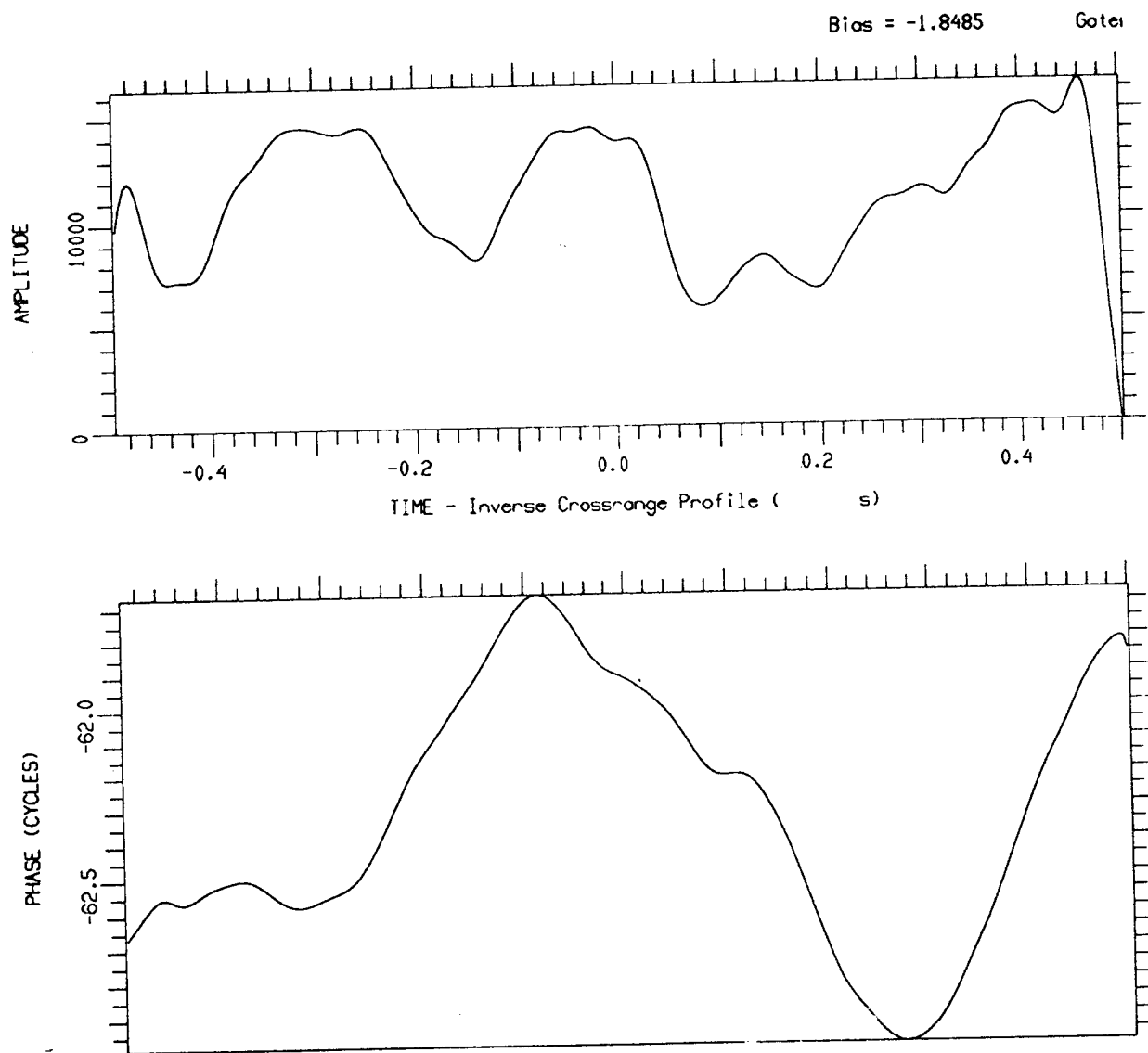


Figure 4.3. Transform of the Image Cut of Figure 4.2.

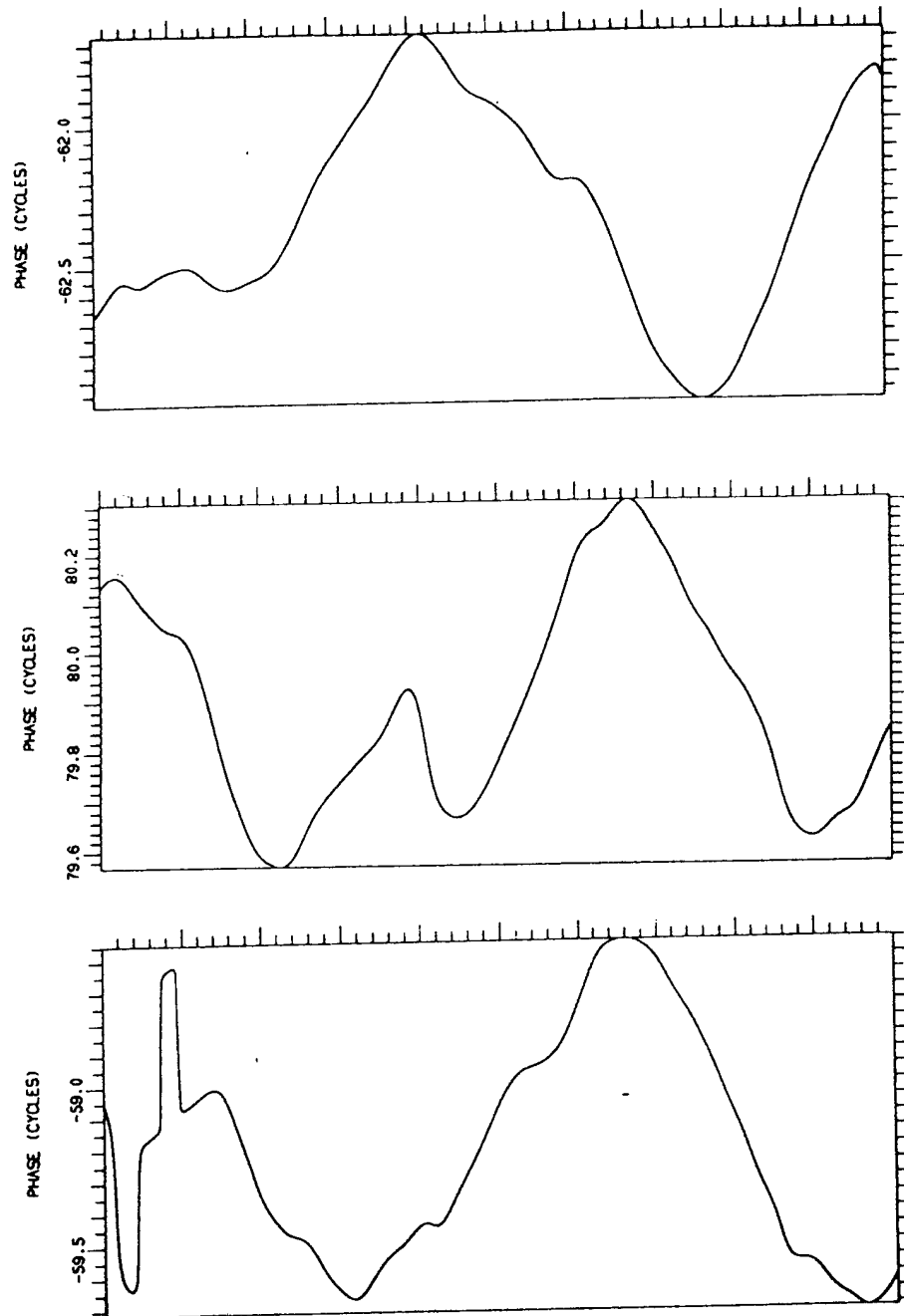


Figure 4.4. Phase Functions of the Transforms of Range Gates 15.5 (Bottom), 21.6 (Middle), and 32.9 (Top).

function of the top plot is radically different. The expression radical is justified because the phases swing over about one cycle. This implies a large degree of response smearing, as verified by Figure 4.1.

The question now is whether or not these phase functions represent rigid body rotation. In other words, does the phase smoothly change with range? Figure 4.5 shows the transforms of the scatterers in Range Gates 28.6 and 25.5. The phase for Gate 28.6 behaves like that for Gate 32.9, while that for Gate 25.5 behaves like that of Gates 21.6 and 15.5. This abrupt change indicates nonrigid body motion. This completes the analysis of the motion behavior of the vehicle. Based on the three phase functions of Figure 4.4, which characterize the motion behavior over the length of the vehicle, we must now decide which specific imaging interval to use.

4.3 CHOICE OF THE IMAGING INTERVAL

The simplest choice of the imaging interval would be one for which the phase functions of all three scatterers are about linear, since this implies proper compression of the responses. Let us for the moment ignore the fact that the intervals with linear phase in Figure 4.4 do not coincide, and consider one phase function at a time.

The question becomes, is any interval with linear phase long enough to allow detecting scatterers other than the dominant one, or would we have such low crossrange resolution that only the range profile of the target would be measured? In an application in which crossrange resolution is obtainable, we must not be satisfied with a range profile. This might suggest a test where we take the FFT of the amplitude/phase functions over each interval with linear phase and determine whether more than one response is visible in the transform. As pointed out in [4], this would utilize only half the available resolution. To make full use of the inherent resolution capability, we must determine whether the phase function contains the regular modulation pattern indicative of a second or perhaps third scatterer. On examination of the top plot of Figure 4.4 we find that during each interval of "linear" phase such a phase modulation is either absent or noiselike. The imaging interval thus would be too short to achieve a meaningful crossrange resolution. Moreover, the imaging interval would have to be chosen so that all three phase functions are linear within the same interval. If this is done, in accordance with

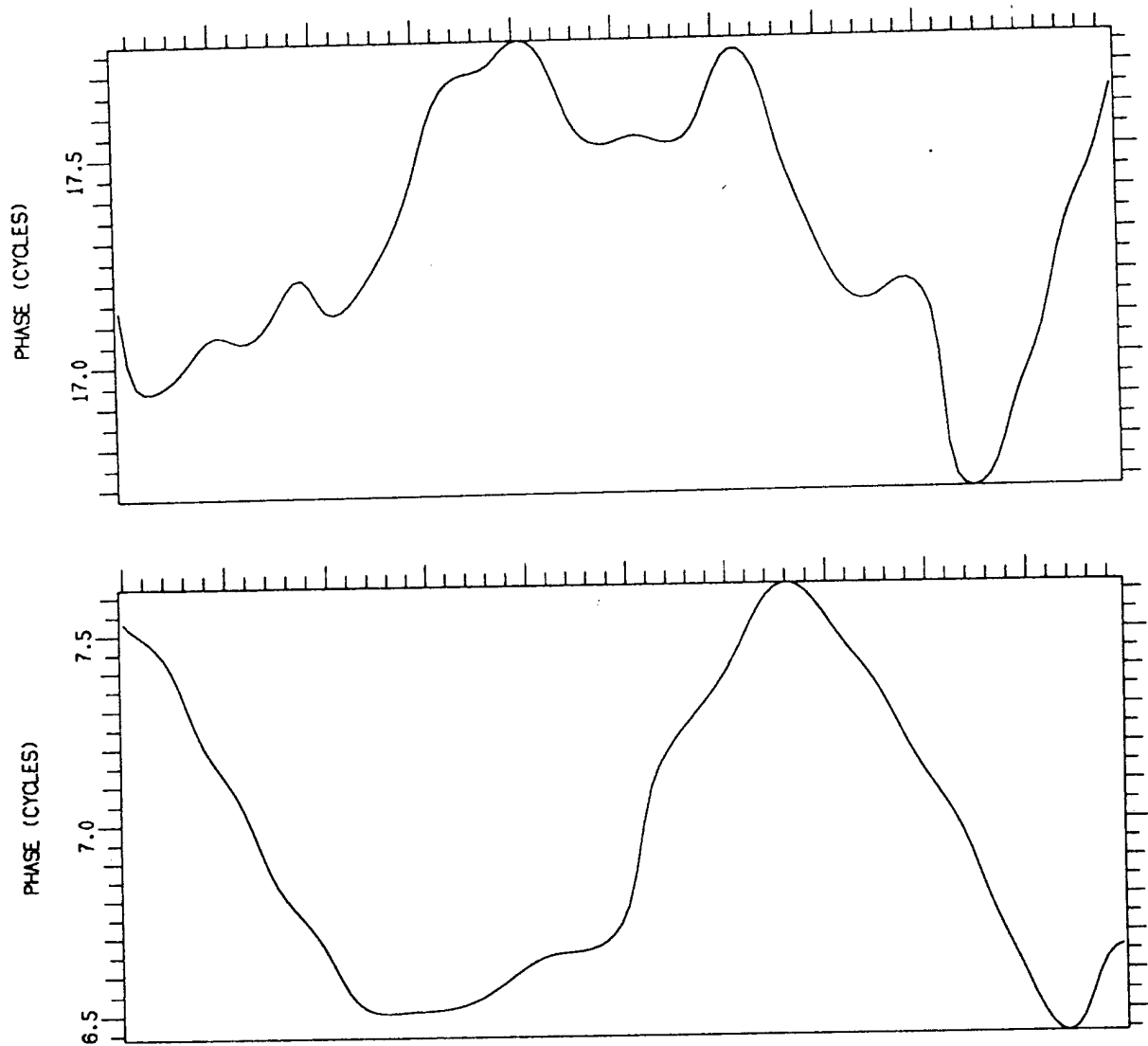


Figure 4.5. Phase Functions of the Transforms of Range Gates 25.5 (Bottom) and 28.6 (Top).

Figure 4.4 the imaging interval would be about 10% of the one displayed in the figure. We would obtain only the range profile of the target.

If there are secondary scatterers present with a high crossrange separation, their presence will be recognized from the modulation of the phase function in the intervals over which the phase function is relatively straight. However, if the crossrange separations are lower, the phase modulation introduced by the bending will mask the modulation from other scatterers. Thus, we cannot understand the situation from an examination of the phase functions of Figure 4.4, and we cannot select an imaging interval based on these phase functions. Instead, we must process over an interval extending over the bending-induced phase variations, which must be removed (without also removing the scatterer-induced phase variations) by an additional motion compensation. How long a processing interval should we choose? The best approach is to start with the entire interval, and reduce it if problems appear, but only to the degree forced by the problems. For our demonstration we will process over the entire 2.7 s, evaluate the result, and if necessary reduce the imaging time on the basis of this analysis.

4.4 MOTION COMPENSATION OF THE SCATTERER IN RANGE GATE 32.9

We arbitrarily select the range gate considered earlier, which is Range Gate 32.9, with the amplitude and phase functions of Figure 4.3. Figure 4.4 shows that the phase functions of the other two major scatterers have similar characteristics, and hence should be analyzable in the same way. If we wanted to generate a focused image, if some problem should force a reduction of the imaging interval for one of the range gates with strong dominant scatterers, the reduction would have to be applied to all range gates. Since we want to "focus" responses instead of the image, and must use different motion compensations over the target extent, we can use different imaging intervals in the different range gates. Again, an example of adaptivity. Our association of measured responses with target features must, of course, allow for the different motion compensations and imaging intervals. They can be incorporated into a deformable template based approach.

The large excursions of the phase function are caused by the motion compensation residual. If only a single scatterer were present in this range

gate, the phase function would truly represent the motion of the scatterer. Thus we could fit a flexible spline function to the phase function of Figure 4.3, and use it for motion compensation. However, the wiggles in the amplitude and phase functions imply that the response is not due to a single scatterer. For a proper motion compensation, we then must fit the spline only to the phase function due to the dominant scatterer, but not to the modulations caused by other scatterers. This is generally not possible to the desired accuracy. The fitted spline will pseudo-periodically deviate from the phase function of the dominant scatterer, and these deviations will cause crossrange sidelobes. They will simulate responses where there are none.

Before we can proceed, we must again test the situation. The phase function of Figure 4.3 contains phase "jumps" introduced by other scatterers, but they are difficult to recognize. Thus we will try a motion compensation based on the phase function as it is, without correcting the phase jumps. This fit is shown in Figure 4.6, and the transform after subtracting the spline fit from the phase function is shown in Figure 4.7. We clearly see a dominant response. However, the secondary responses are so low that we cannot readily distinguish between genuine responses and sidelobes generated by the errors in the spline fit.

When the same procedure is repeated after attempting to correct the phase jumps, the resulting transform is not significantly different from that of Figure 4.7. There are more sophisticated ways of trying to determine the component of the phase function of Figure 4.3 introduced by the dominant scatterer, so that the spline function may be fitted only to that component. However, in a situation where any secondary scatterers are so weak these procedures are not promising. Instead of pursuing such complicated procedures, we will give another illustration of adaptive processing.

The problem at this point is that the secondary scatterers are weak compared with the dominant scatterer. However, in that case we can take the FFT of the amplitude function alone, which does not contain effects from the motion compensation. This will generate responses due to Doppler differences between all scatterers, but if one scatterer is dominant the only significant responses will be at the Doppler differences between secondary scatterers and the dominant scatterer. Thus we obtain the separations of secondary scatterers from the dominant one, but because the FFT of the amplitude function is

symmetric, we do not know whether the secondary scatterers are at lower or higher crossranges than the dominant scatterer.

The FFT of the amplitude function is shown in Figure 4.8. By comparison with Figure 4.7 we see that in both amplitude plots there are secondary responses indicated in Gates 125, 126, 132, and 133, but the responses with farther separations from the dominant response in Figure 4.7 are not present in Figure 4.8. These are thus caused by the inaccuracies of the motion compensation. However, the noncoherent transform of Figure 4.8 does not provide the information whether the genuine responses are on the left side, the right side, or on both sides of the dominant response. Since in Figure 4.7 the sidelobes generated by the motion compensation residual are of the same magnitude as the genuine responses, the information cannot be obtained from Figure 4.7 either.

The solution lies in understanding the source of the problem. By examining Figure 4.6 we see that the major secondary response disappears beyond a time of 0.1 s (the periodic amplitude modulation disappears). Thus, at least in this gate, we should process only from -0.5 to 0.1 s. We use this section of Figure 4.6, and remove the phase "jumps" occurring at the times of the amplitude minima to whatever accuracy is achievable. The result, together with the spline fit, is shown in Figure 4.9 on a renormalized scale. When the phase is compensated with the indicated spline and the transform is taken, we obtain Figure 4.10. Now we clearly see a genuine response about 2 gates to the left of the main response, the low-level responses being sidelobes generated by the motion compensation. For a verification of the phase compensation we also apply it to Range Gate 28.6, and obtain a perfectly focused response. As we would expect from the phase functions of Figure 4.5, the compensation does not work well for Range Gate 25.5. An alternative approach to resolving the signs of the separations between dominant and secondary scatterers, usable when the phase "jumps" are more difficult to remove, is discussed in the Appendix.

4.5 FURTHER PROCESSING OF THE VEHICLE

We perform the same type of processing in the range gates with the other strong responses, for which the phase functions are shown in the middle and lower plots of Figure 4.4. We note that the middle plot has one large phase

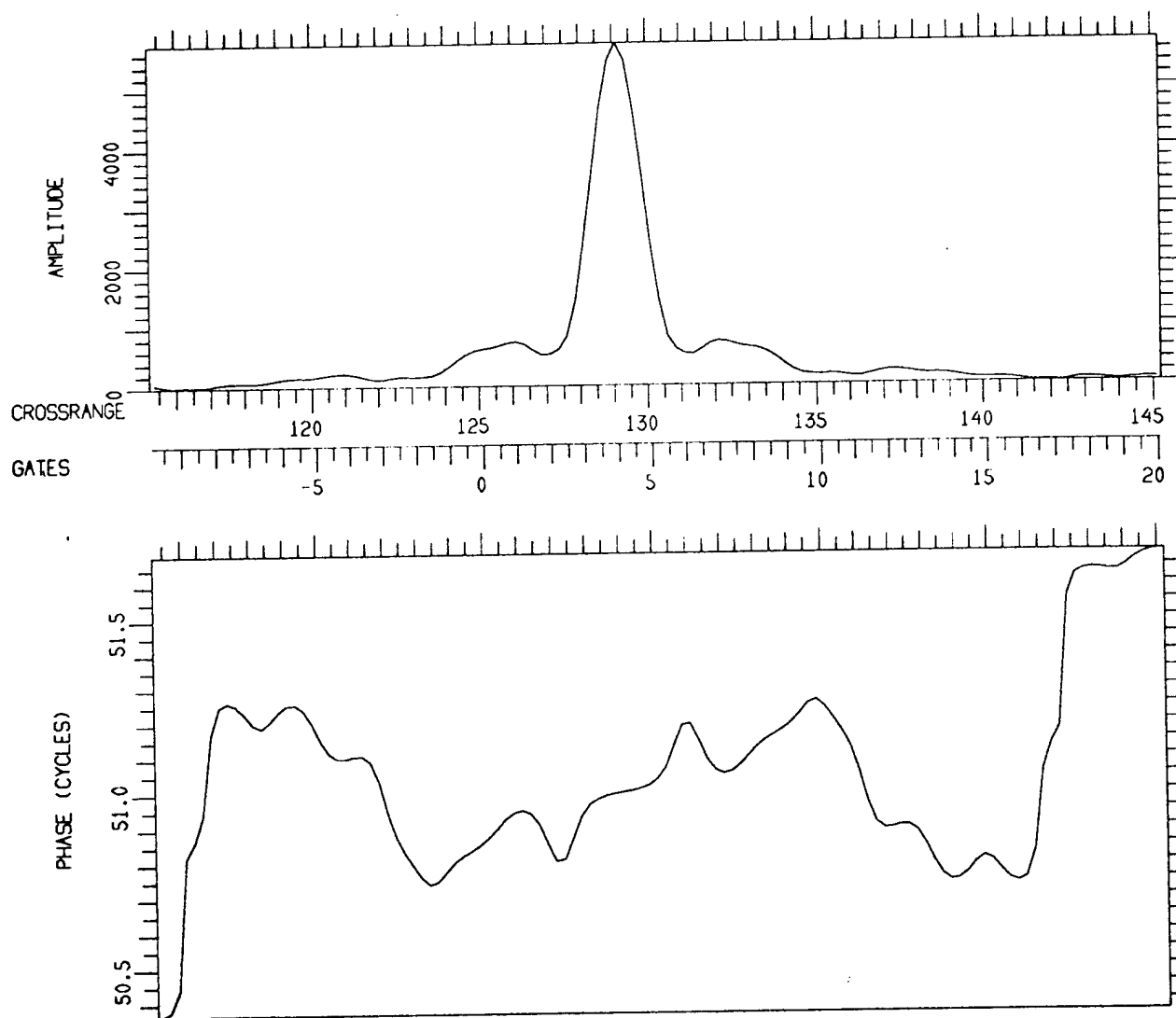


Figure 4.8. FFT of the Amplitude Function of Figure 4.3.

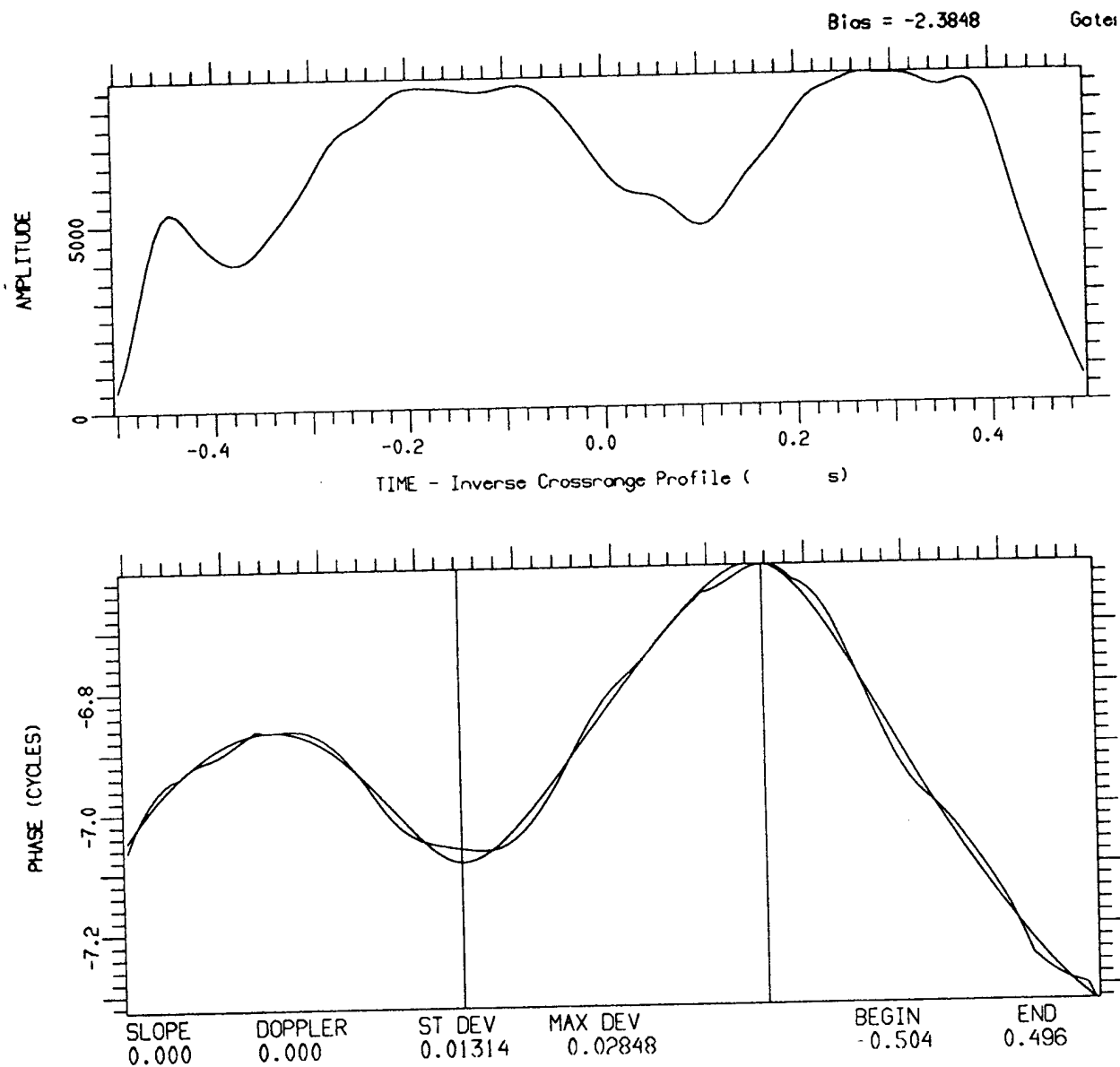


Figure 4.9. Spline Fit for the Shortened Time Interval.

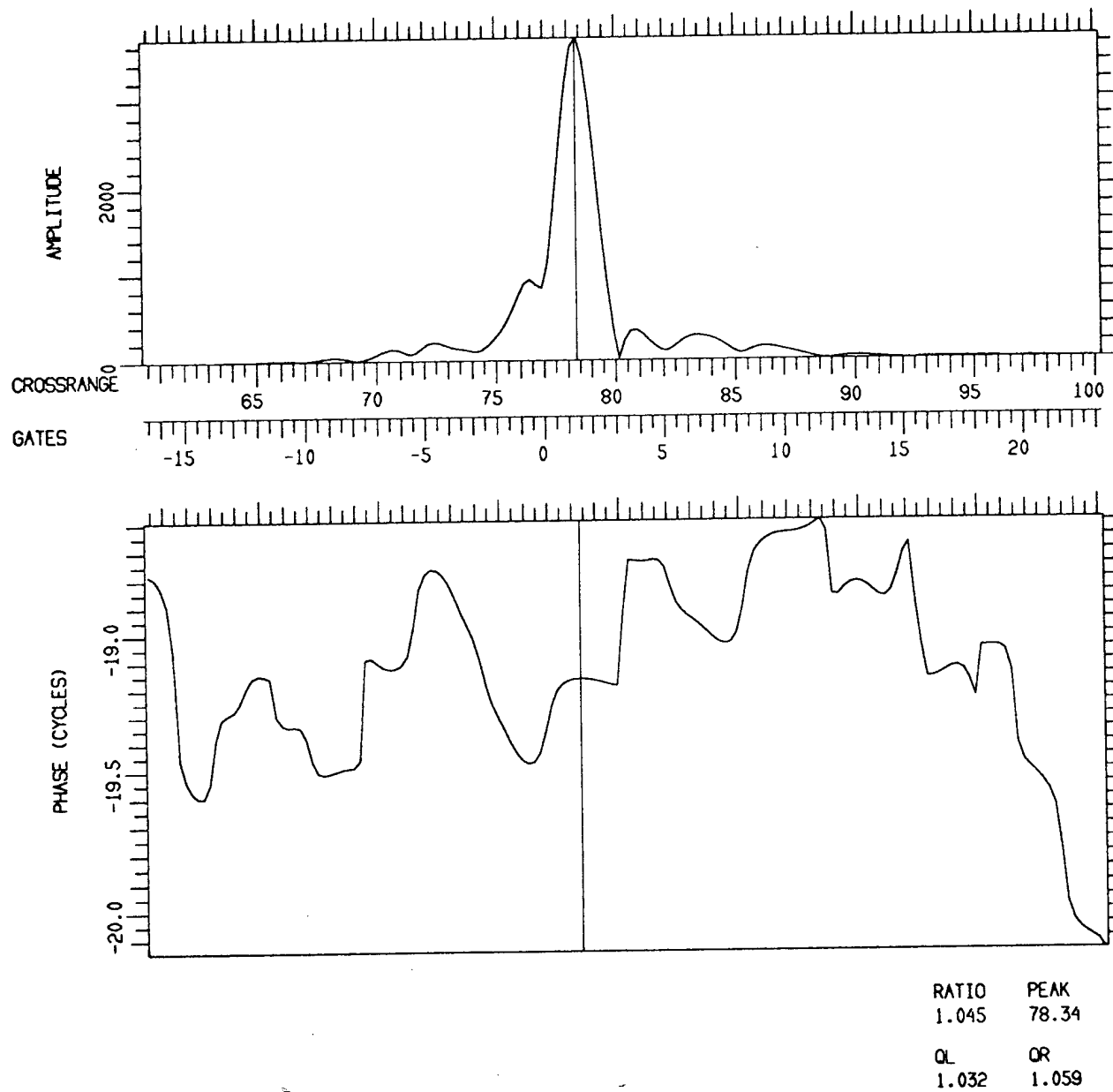


Figure 4.10. Transform of Figure 4.9 After Phase Compensation.

jump (which correlates with an amplitude minimum), so that this phase jump must be taken out before fitting a spline. The bottom phase function has several large phase jumps, which also must be corrected before the fit. This allows us to determine the scatterers in the corresponding range gates. We will not proceed to the actual comparison with the locations of the scatterers on the vehicle because we do not have sufficient information on the vehicle.

Having established motion compensations in range gates with dominant scatterers, or just in range gates where the conditions permit good motion compensations, we can use the same motion compensations in nearby range gates. By measuring the widths of the responses we can determine whether or not a motion compensation is good enough to permit measurements on the scatterers. Beyond the range interval within which a particular motion compensation is usable we have to go through a new motion compensation process.

To show how small the range interval accommodated with one motion compensation can be, in Figure 4.11 we show the peaks plot of the vehicle when the motion compensation of Figure 4.9 is applied to the entire reduced duration image. In Range Gate 32.9, the responses immediately to the left and right of the dominant response are the ones identified earlier. Note that they do not appear in exactly the same range gate, which indicates that the aspect angle is not exactly tail-on. However, the responses in the other range gates are drastically defocused, because of the flexing of the vehicle. We note that the responses in Range Gate 29 are also focused by the same compensation as used for Range Gate 32.9.

4.6 A FLATBED TRUCK ON THE SAME ROAD

We briefly consider a flatbed truck moving behind the first vehicle with the same low speed. The point to be made is that the radar observes two vehicles under essentially identical conditions, and yet the second vehicle cannot be processed in exactly the same fashion as the first.

In Figure 4.12 we show the peaks plot image of the flatbed with the same imaging interval and range and Doppler centroid compensation algorithms as used for the refueling truck. Figure 4.13 shows the transform of the image cut in Range Gate 23.9. This range gate was selected because an image cut along the long axis of the image shows that the response in this range gate was sharpest. The main characteristic of the phase function of Figure 4.13 is

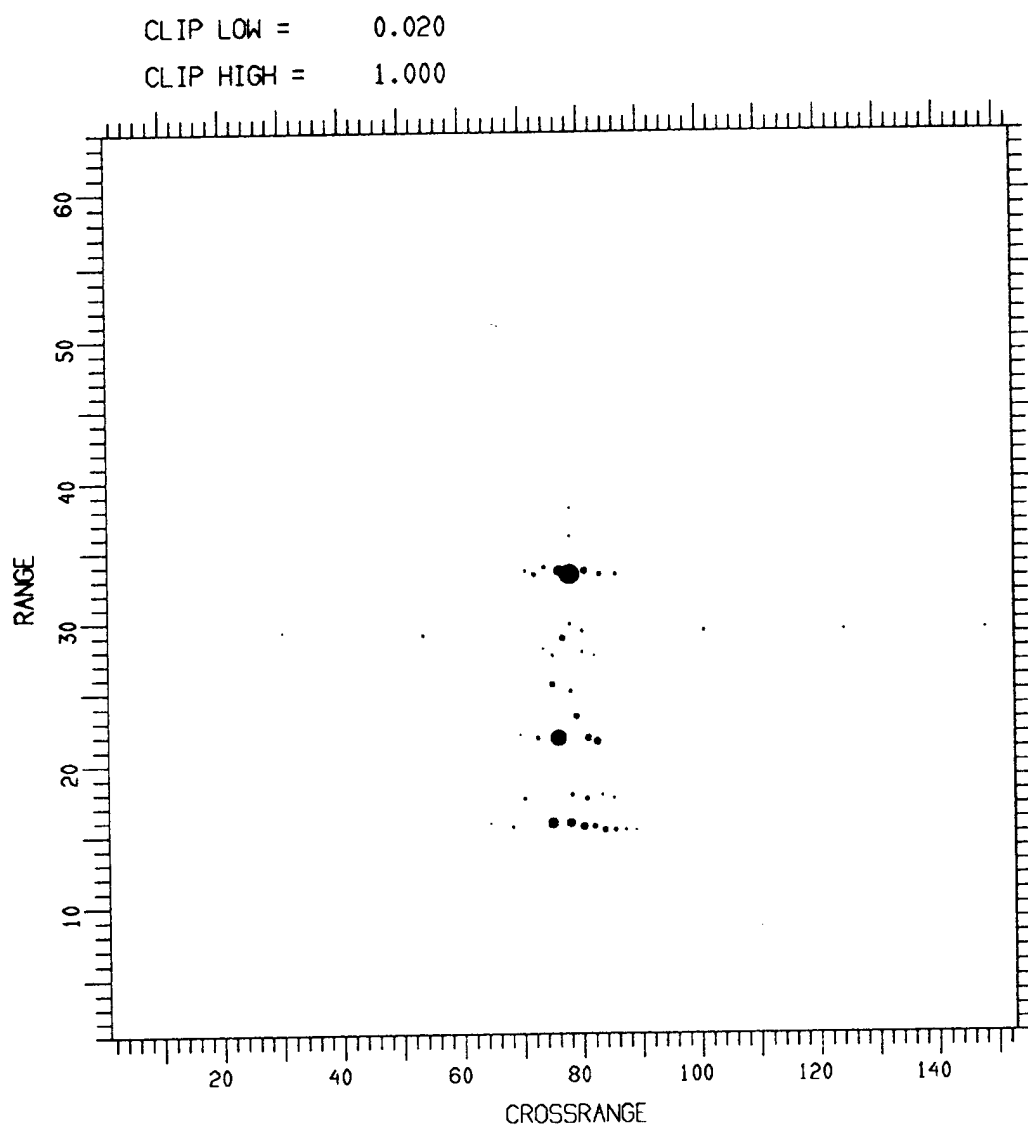


Figure 4.11. Peaks Plot for a Compensation in Accordance with the Scatterer in Gate 32.9.

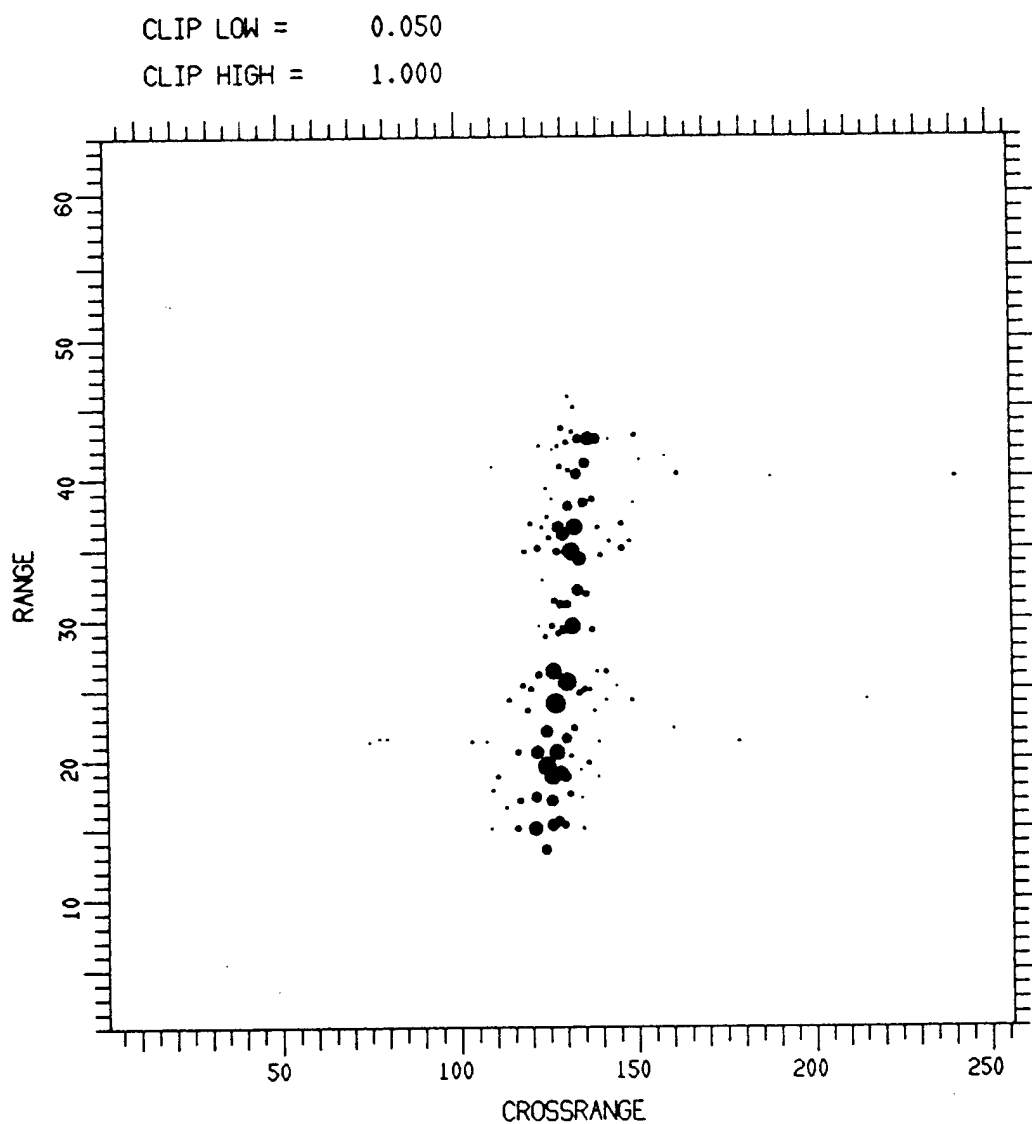


Figure 4.12. Peaks Plot Image of the Flatbed After Centroid Compensation.

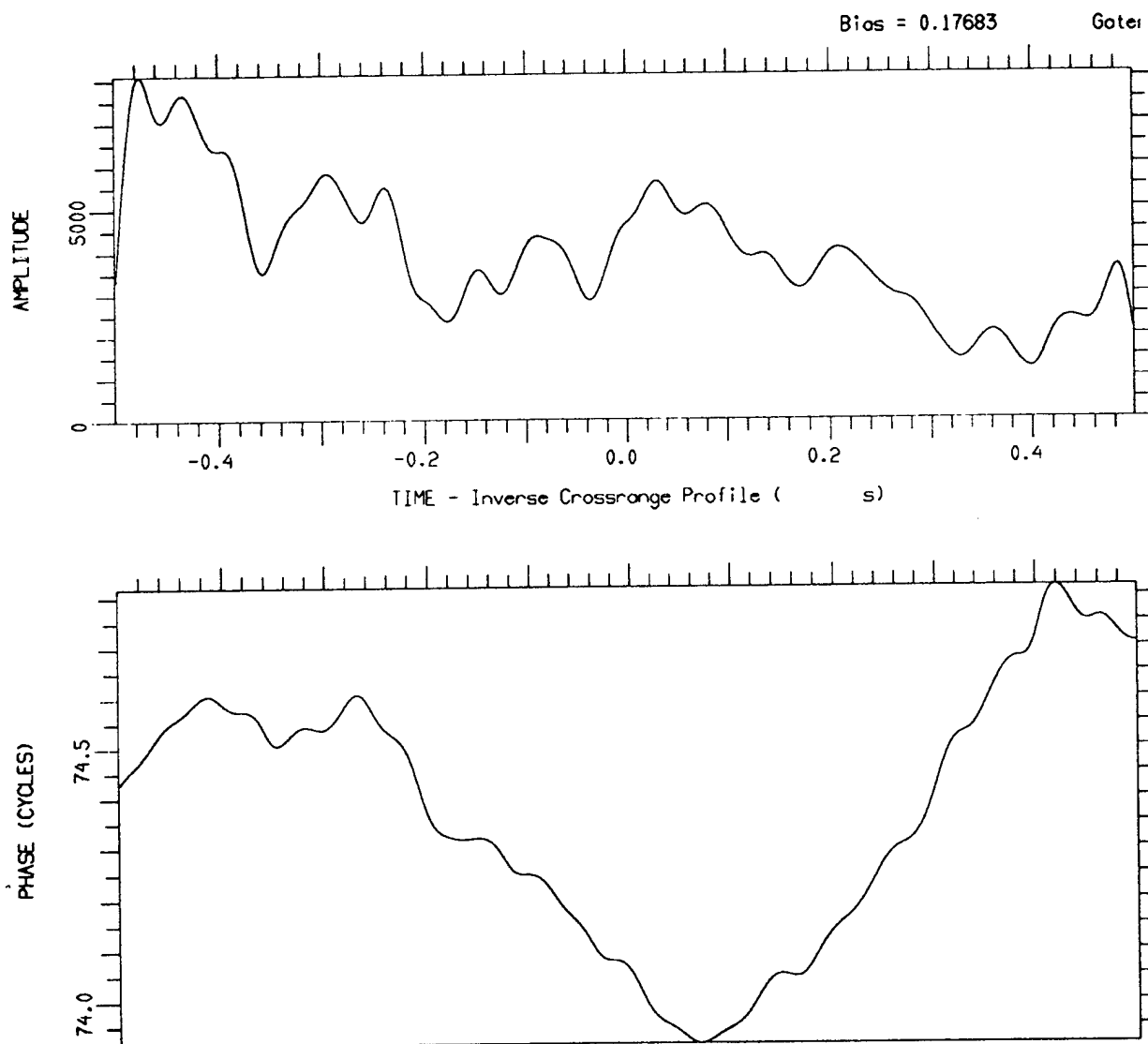


Figure 4.13. Transform of the Image Cut in Range Gate 23.9.

the sharp break of the phase slope. Since the value of the phase slope corresponds to crossrange position, we have the main cause of the spreading of the response.

Before proceeding with the compensation, we must check the range gates at the end of the truck, to make sure that the scatterers do not drift out of their range gates. In our first example, as shown by Figure 4.3, this was not a problem. Figure 4.14 shows the transform of the image cut in Range Gate 42.8. As marked by the crosshair, the amplitude drops to a very low value beyond a normalized time of 0.32 s. Such a sudden drop is typical for the case when the scatterer moves out of the range gate. Note that only in the rare case when the drift of the scatterer is very slow can one again find the scatterer response in the adjacent range gate. More typically the drift leads to a smearing of the response into the background. The same effect, but at the other end of the time scale, can be found for scatterers at the other end of the truck.

Another decision must be made now. Do we try to prevent the loss of the scatterers near the ends of the imaging interval by some method equivalent to polar format processing, or do we simply reduce the imaging interval of the image of Figure 4.12 to exclude the problematic parts? In principle, we can track the vehicle in the SAR image, obtain an estimate of the aspect angle and the angular change over the interval, and from this obtain an estimate of the crossrange resolution. Then we can decide what imaging interval is needed. Since our interest here is in the principles, we reduce the imaging interval.

After selecting the time interval such that the amplitude drops for the ends of the truck are avoided, we compensated the new image with the phase function derived from the scatterer in Range Gate 24. This then gives a single-scatterer motion compensation for the entire image, analogous to the compensation that produces Figure 4.11 (except that there a scatterer at the end of the truck was used). The resulting peaks plot image is shown in Figure 4.15. The image appears well focused to the eye, and an examination of the individual responses shows that even the responses at the two ends of the truck are well focused. This means that bending effects are negligible for this particular vehicle under the existing circumstances. This image can now be analyzed to determine scatterer positions.

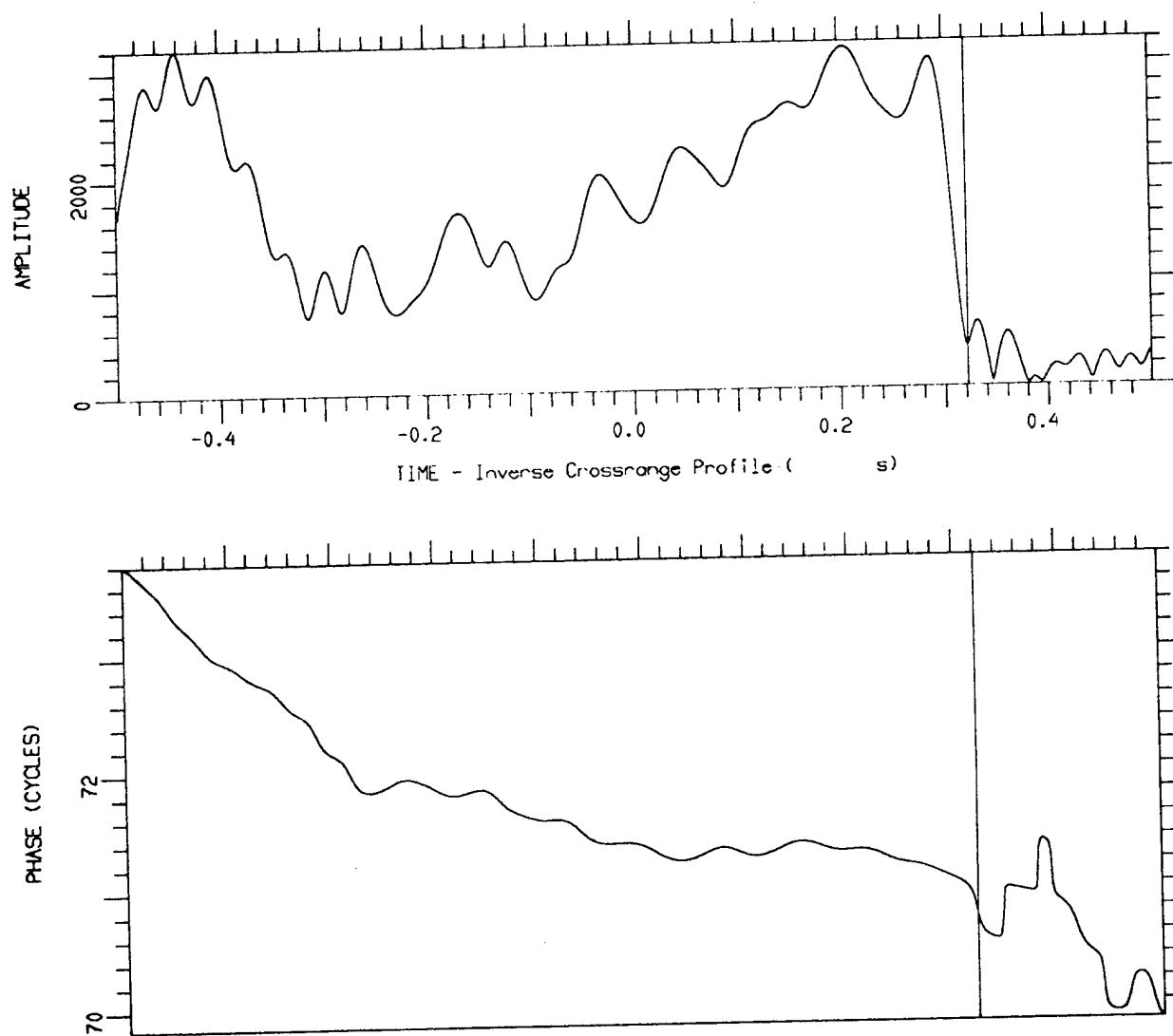


Figure 4.14. Transform of the Image Cut in Range Gate 42.8.

CLIP LOW = 0.100
CLIP HIGH = 1.000

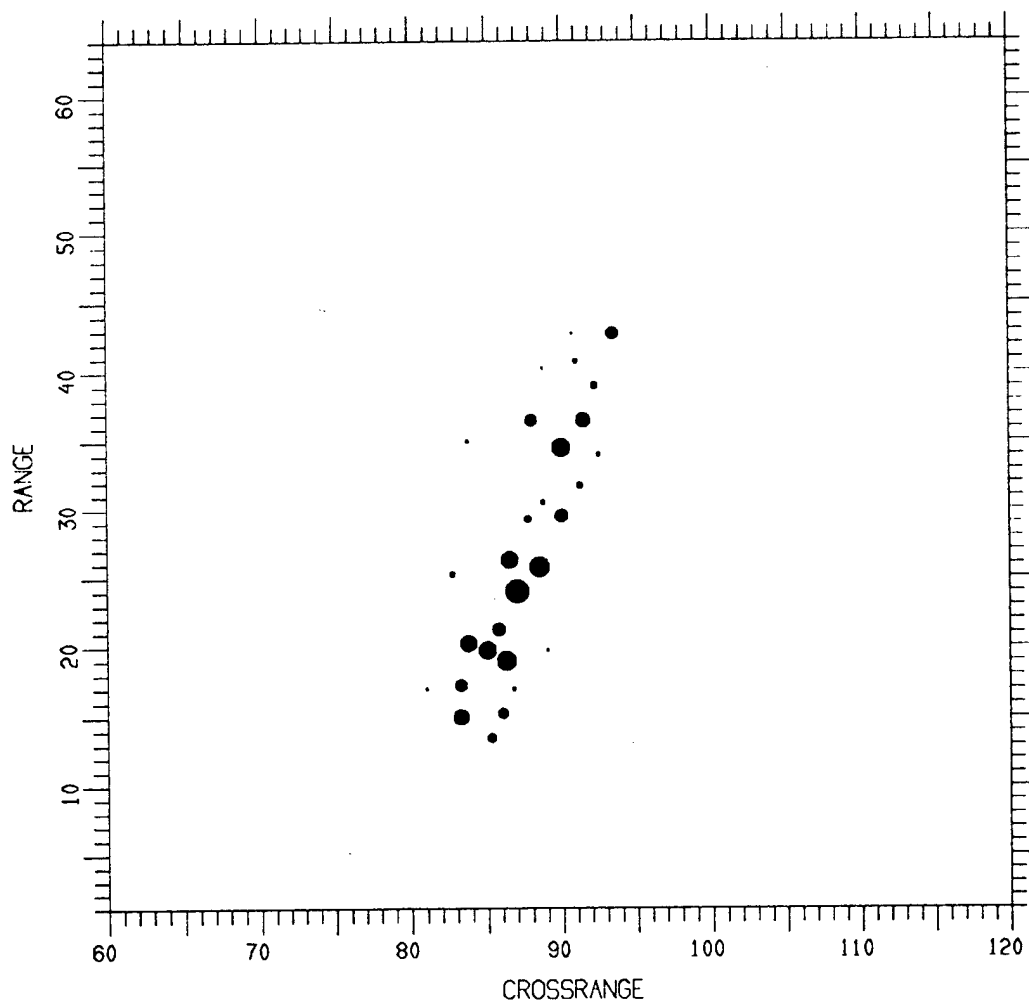


Figure 4.15. Peaks Plot Image of the Flatbed After Reducing the Imaging Interval and Compensating a Single Scatterer.

4.7 ANOTHER REFUELING TRUCK DURING A THREE-POINT TURN

The point of this section is that every situation requires different processing, so that ISAR imaging must necessarily be an adaptive process. We give another brief summary of the same type of refueling truck used for the first example, but during a three-point turn.

We again start from the 2.7 s image formed with a range centroid and Doppler centroid motion compensation. The resulting peaks plot image is shown in Figure 4.16. The large number of dots indicates a poor motion compensation. Thus we would want to find a well resolved (even though perhaps smeared) response, take its transform, and derive the motion compensation from the phase of the transform. The problem is that no response of the image allows us to do that. An examination of the stronger responses shows that the motion compensation is relatively good in that the transforms of the individual responses give amplitude/phase patterns nearly as expected from a single or a pair of scatterers, but not quite good enough for measuring the locations of the scatterers.

In such a situation we use the following reasoning. Although the responses of the image of Figure 4.16 are almost well focused, so that the crossrange spread of the image is determined by the scatterers rather than smeared responses, we see that the crossrange spread is about 70 gates. Hence, if this is a vehicle of typical dimensions, the crossrange resolution cell is much smaller than needed for identification. Thus we can reduce the imaging interval, choosing the best part of the imaging interval used with Figure 4.16. The choice of the best part of the imaging interval again would be simple if we could find a well resolved response. Since this is not the case, we will define the new interval from the response of a pair of scatterers, choosing the response that gives the best approximation to the amplitude/phase pattern from two scatterers [1].

Figure 4.17 shows the transform of the strongest response in Range Gate 31.5. With a perfect motion compensation the central part of the phase function would be linear. Thus we choose an imaging interval over which the phase function is as linear as possible, without reducing the imaging interval so much that crossrange resolution becomes inadequate. The choice indicated in the figure appears reasonable. The corresponding peaks plot image is shown in Figure 4.18 with an expanded scale. Taking transforms of the responses of

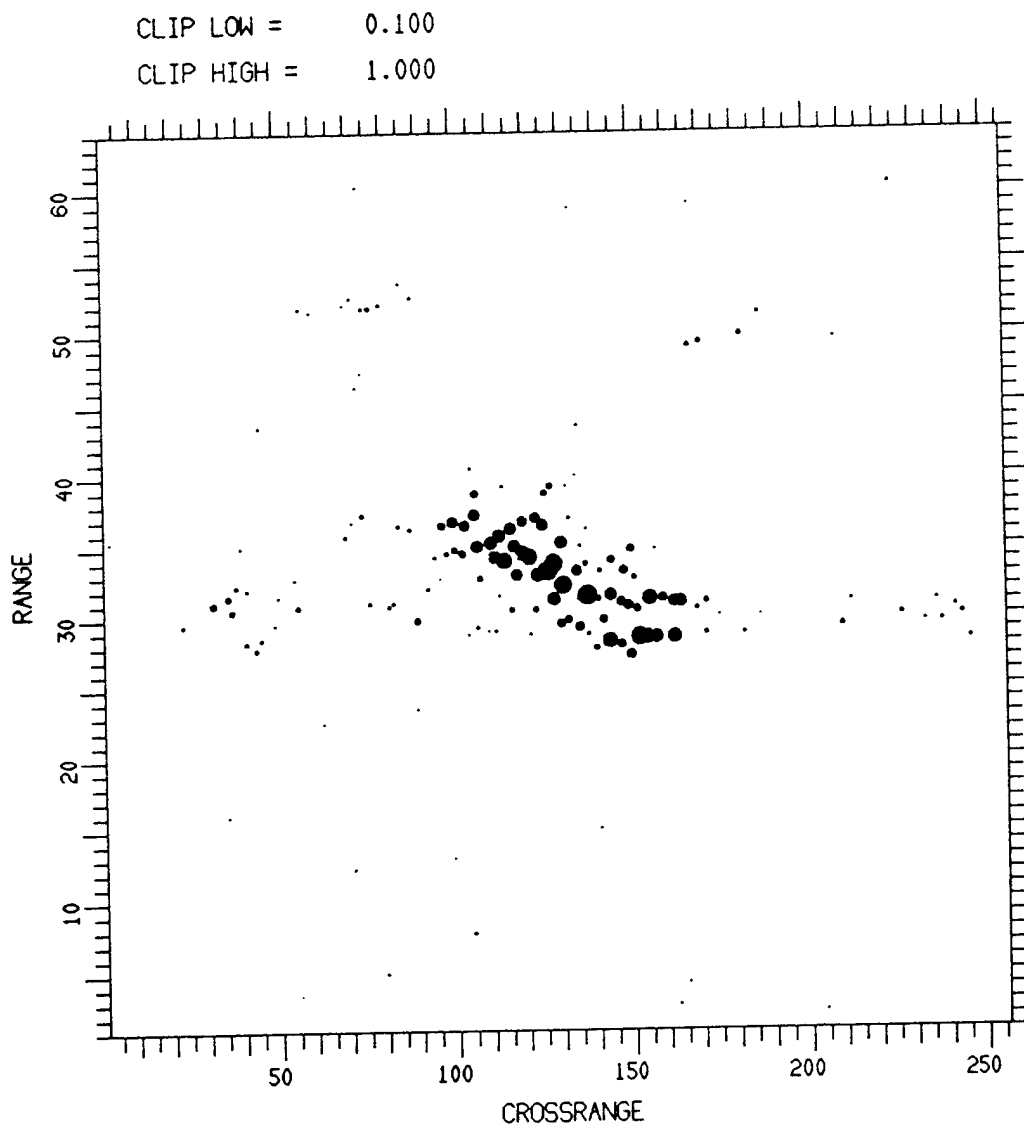


Figure 4.16. Peaks Plot Image of a Refueling Truck
During a Three-Point Turn.

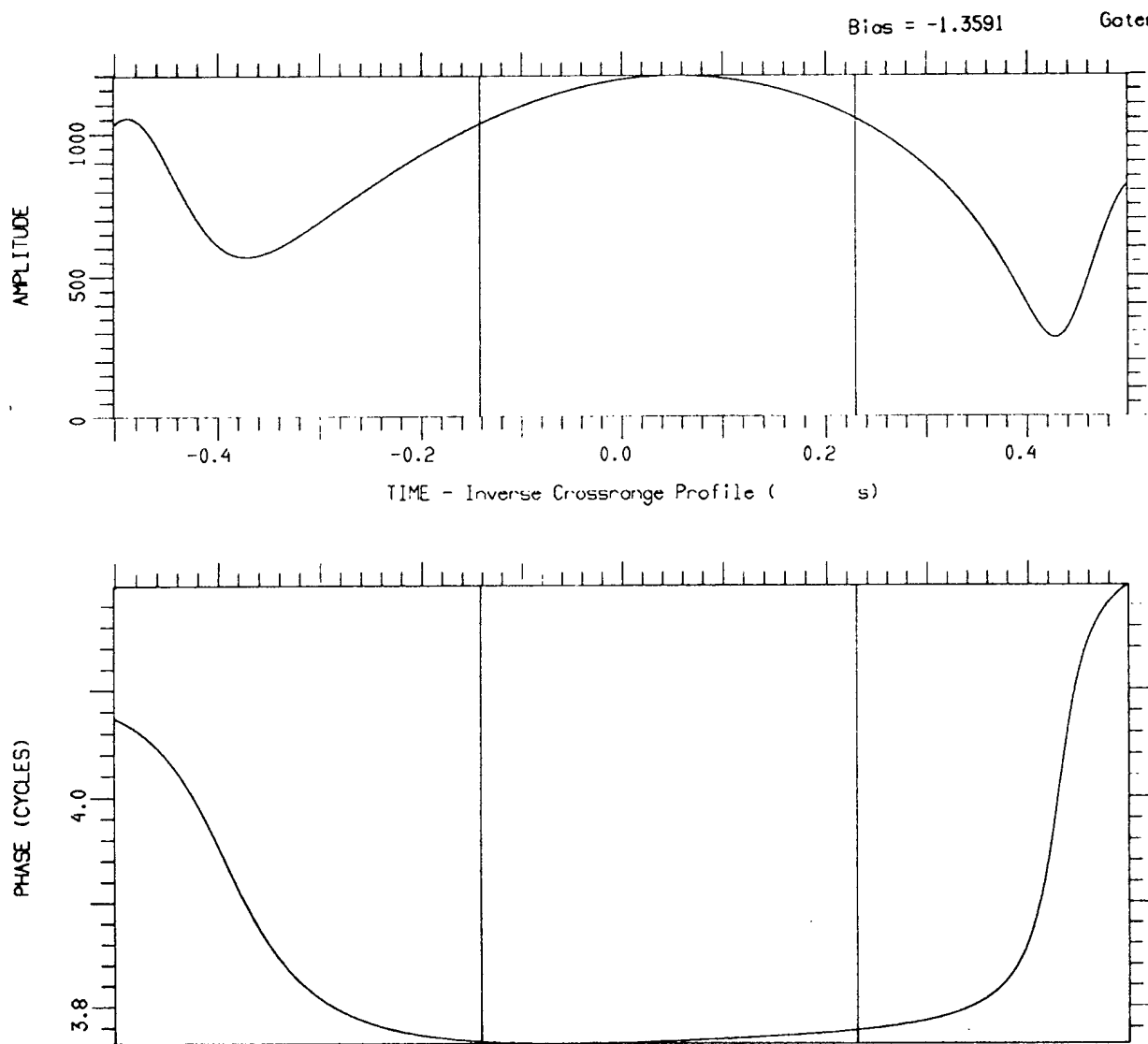


Figure 4.17. Transform of the Response in Range Gate 31.5.

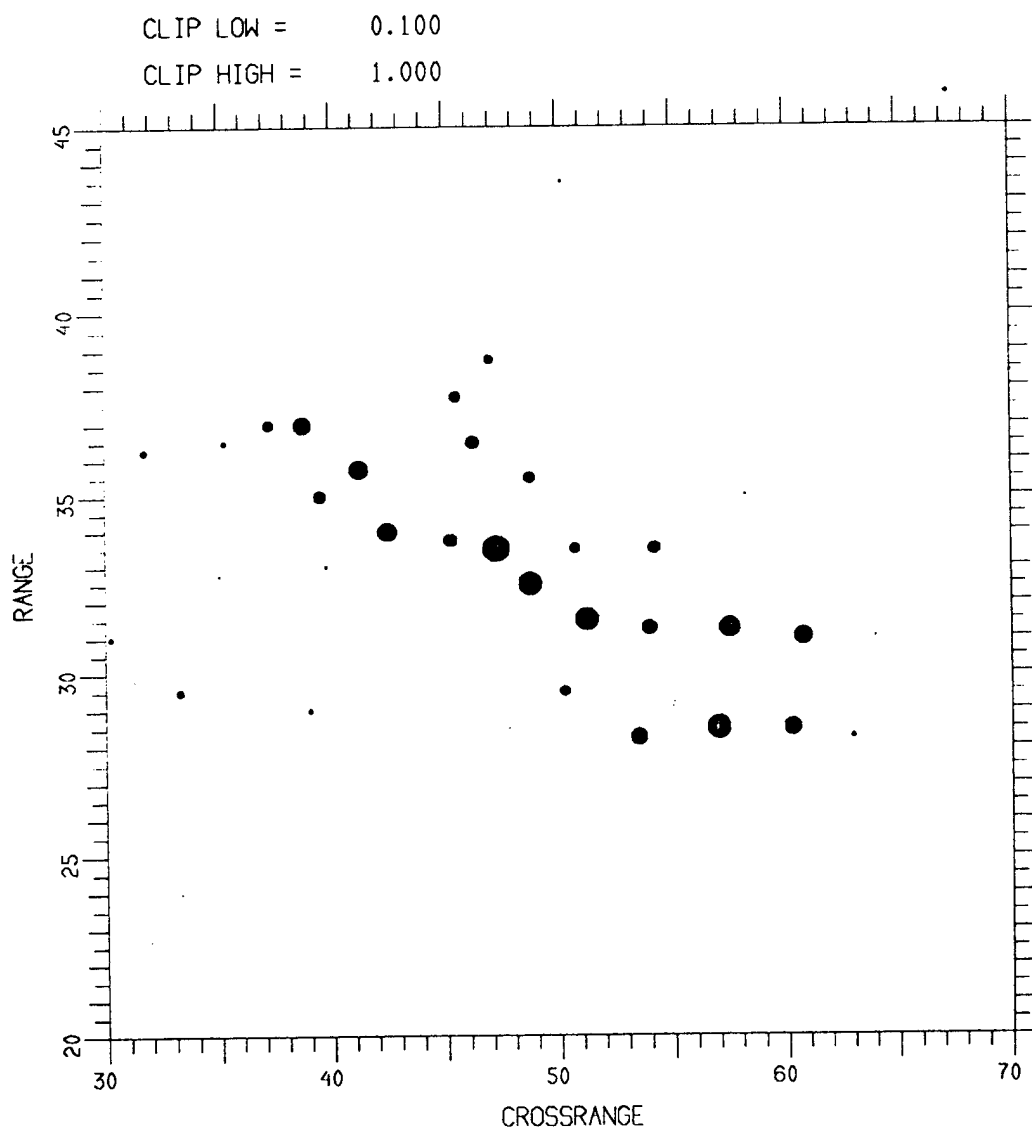


Figure 4.18. Peaks Plot Image with Reduced Imaging Interval.

the new image gives good approximations to the amplitude/phase patterns from single scatterers or pairs of scatterers, so that no further motion compensation is needed. This is true for the responses over the entire image, implying that the flexing of the vehicle is negligible in this case (it was very significant in our first example when the same vehicle was traveling slowly on a paved road).

Actually, the choice of the imaging interval in accordance with Figure 4.17 is not acceptable without a further test. It could happen that one or both of the scatterers contributing to the response has a shifting phase center, which would also introduce a curvature into the phase function. Thus we must test several responses so as to determine that the pattern of Figure 4.17 is not unique to the chosen response.

4.8 ASSESSMENT AND RECOMMENDATIONS

We have considered three ground vehicles, two traveling slowly on the paved road, and a third vehicle of the same kind as the first during a three-point turn. Each situation has required different processing steps to form an image with "focused" responses, with a variety of tests needed to determine what processing is to be used. Thus, a high degree of adaptivity is needed when moving ground vehicles are to be identified.

For the first vehicle, we have shown that one must and can focus the responses of an ISAR image even when the scatterers are moving differently in different parts of the vehicle, with the irregularities of the motion large enough to cause severe smearing of the responses. We can focus the responses even though the imaging interval extends over more than a motion cycle of the vehicle. However, responses in different range gates require different focusing functions. The flatbed truck shows an abrupt change in its Doppler, but flexing is insignificant. This is also true for the vehicle during the three-point turn, but resolution problems require still different processing. At many points during the processing we must analyze the situation and then tailor the next step to the particular vehicle and its behavior. We have a number of processing tools and on the basis of tests must continually decide which tool to use and in which manner, then analyze the results before making the next decision. This is a complicated process and requires considerable

work to automate, but without this type of adaptive processing we cannot generate an "image" of acceptable quality.

The examples considered under this program are very benign, because they involve four ground vehicles with excellent behavior: Slow speeds, smooth motions, and paved surfaces. Despite these benign conditions the processing that allows extracting sufficient information for vehicle identification (not just forming some kind of image that appears to be focused) is rather sophisticated. Even more sophisticated processing will be required if the vehicles move fast, with bouncing, yawing, pitching, rolling, and flexing motions, and if they move on poor roads or even off roads. The development work should be continued for ground vehicles moving under more adverse conditions, and after the appropriate processing procedures are developed they must be automated.

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APPENDIX
DETERMINING SCATTERER SEPARATIONS IN RANGE GATES
WITH RESIDUAL UNCOMPENSATED MOTION

Because moving ground vehicles bend and flex, a motion compensation that is based on a rigid body assumption will generally leave parts of the vehicle with residual uncompensated motion. Typically, this residual motion will not be large enough to cause scatterers to drift from one range gate to another, but will be more than large enough to smear each scatterer response over many crossrange gates, generating multiple response peaks. If a bending/flexing region of the vehicle contains a scatterer that is sufficiently well resolved or enough stronger than its neighbors, that scatterer can be used to derive a compensation for that region of the vehicle. Unfortunately, a bending/flexing region need not be large, and such a scatterer may not be available.

This appendix describes a technique, applicable when such a scatterer is not available, for determining scatterer crossrange separations. It relies on using two nearby range gates undergoing similar bending/flexing. First, we take the Fourier transform of each range gate. The amplitude function of each resulting signal contains information determining the absolute scatterer separations in the corresponding range gate, but not the signs of the separations. The absolute separations are most easily extracted by examining the transform of the signal amplitude, as in Section 4.4.

In order to determine the signs of the separations, we multiply the signal from one range gate by the complex conjugate of the signal from the other. The residual uncompensated common motion cancels out of this complex product signal. If the two range gates have different scatterer separations or relative amplitudes, the product signal allows us to determine the signs of the separations. This is shown below.

Consider the case where we have two nearby range gates containing scatterers undergoing the same unknown motion. The signals for these gates can be written as

$$S_j(t) = \sum_{k=1}^{N_j} A_{kj} \exp[i(\omega_{kj}t + \phi_{kj})] \exp[i\phi_m(t)] \quad (A.1)$$

where j denotes the gate, there are N_j scatterers in gate j , and $\phi_m(t)$ is the common phase motion.

The power in a gate is

$$\begin{aligned} P(t) &= S_j(t) S_j^*(t) = \sum_{k,n} A_{kj} A_{nj} \exp[i(\omega_{kj}t + \phi_{kj})] \exp[-i(\omega_{nj}t + \phi_{nj})] \\ &= \sum_{k,n} A_{kj} A_{nj} \cos [(\omega_{kj} - \omega_{nj})t + \phi_{kj} - \phi_{nj}] \end{aligned} \quad (A.2)$$

This is independent of $\phi_m(t)$, and is real. An FFT will produce a symmetric spectrum, with responses at $\pm(\omega_{kj} - \omega_{nj})$.

Now multiply the signal in one gate with the complex conjugate of that in another:

$$Q(t) = S_1(t) S_2^*(t) = \sum_{k,n} A_{k1} A_{n2} \exp\{i[(\omega_{k1} - \omega_{n2})t + \phi_{k1} - \phi_{n2}]\} \quad (A.3)$$

Because the two sets $\{\omega_{k1}\}$ and $\{\omega_{n2}\}$ are different, $Q(t)$ is not real, and its transform is asymmetric. We can use this asymmetry to measure $\omega_{k1} - \omega_{n2}$ and thereby determine the signs of $\{\omega_{k1}\}$ and $\{\omega_{n2}\}$.

We first illustrate this with synthetic data. Figure A.1 shows the image response from scatterers at Crossrange Gates 33 and 36, plus a quadratic phase drift in time. Figure A.2 shows the corresponding signal. Figure A.3 shows the transform of the power of Figure A.2 with peaks separated by ± 3 Hz.

Figure A.4 shows the image response from scatterers at Crossrange Gates 33 and 28, plus the same quadratic drift. Figure A.5 shows the corresponding signal, and Figure A.6 the transform of the signal power. Peaks there are separated by ± 5 Hz.

Figure A.7 shows the product of the signal of Figure A.2 with the complex conjugate of the signal of Figure A.5. Evidently, the common quadratic phase drift is absent and the signal is complex. Figure A.8 shows the transform of

Figure A.7. It contains responses at frequencies 0, 3, 5, and 8. The response at frequency 0 is generated by the combination of the strongest responses in each of the original gates. The separations and relative amplitudes of the other responses can be used to determine the response separations in Figures A.1 and A.4.

The second strongest response in Figure A.8 is separated from the strongest by 5 Hz (gates). Comparing the relative amplitude and the separation to Figures A.3 and A.6 tells us that this response is generated from the strongest scatterer of Figure A.1 and the secondary scatterer of Figure A.4. Because we took the conjugate of the signal of Figure A.5, the separation of the secondary and primary scatterers of Figure A.4 is the $-(5-0) = -5$ gates.

The response at 3 Hz in Figure A.8 is from the primary scatterer of Figure A.4 and the secondary scatterer of Figure A.1. Thus the separation of the secondary and primary scatterers of Figure A.1 is $(3-0) = 3$ gates. The remaining response of Figure A.8, at 8 Hz, is generated by the secondary scatterers. As expected, its position is $3-(-5) = 8$ Hz.

Will this work with real data? The data must satisfy several conditions. First, the motion of the scatterers in the two gates must be nearly the same. Second, each gate must contain few scatterers for the unscrambling to succeed. Third, the separations or relative amplitudes in the two gates must differ. Fourth, we must have a sufficient signal to noise ratio.

Figure A.9 repeats the image cut in Range Gate 33 of Figure 4.1. Figure A.10 shows the transform of the power of the corresponding signal. Figure A.11 shows the image cut in Range Gate 35 of Figure 4.1, far enough from Range Gate 33 to contain different scatterers, but close enough to have similar motion. Figure A.12 shows the transform of the power of its corresponding signal. Figures A.10 and A.12 show that the absolute separations of the primary and secondary scatterers in Range Gates 33 and 35 are about 3 and 4.5 crossrange gates, respectively.

Figure A.13 shows the product of the signal for Gate 33 and the complex conjugate of the signal for Gate 35. Its transform is given by Figure A.14. The large peak near -1 Hz corresponds to the two primary scatterers. We must search for responses ± 3 and ± 4.5 gates from this. The second strongest response of the figure is near 2 Hz, with an indication of another near

3.5 Hz. Thus, the secondary response in Range Gate 33 is separated from the primary by $-(2-(-1)) = -3$ gates, and the secondary response in Range Gate 35 is separated from the primary by $(3.5-(-1)) = 4.5$ gates. This agrees with the adaptive analysis of Section 4.4.

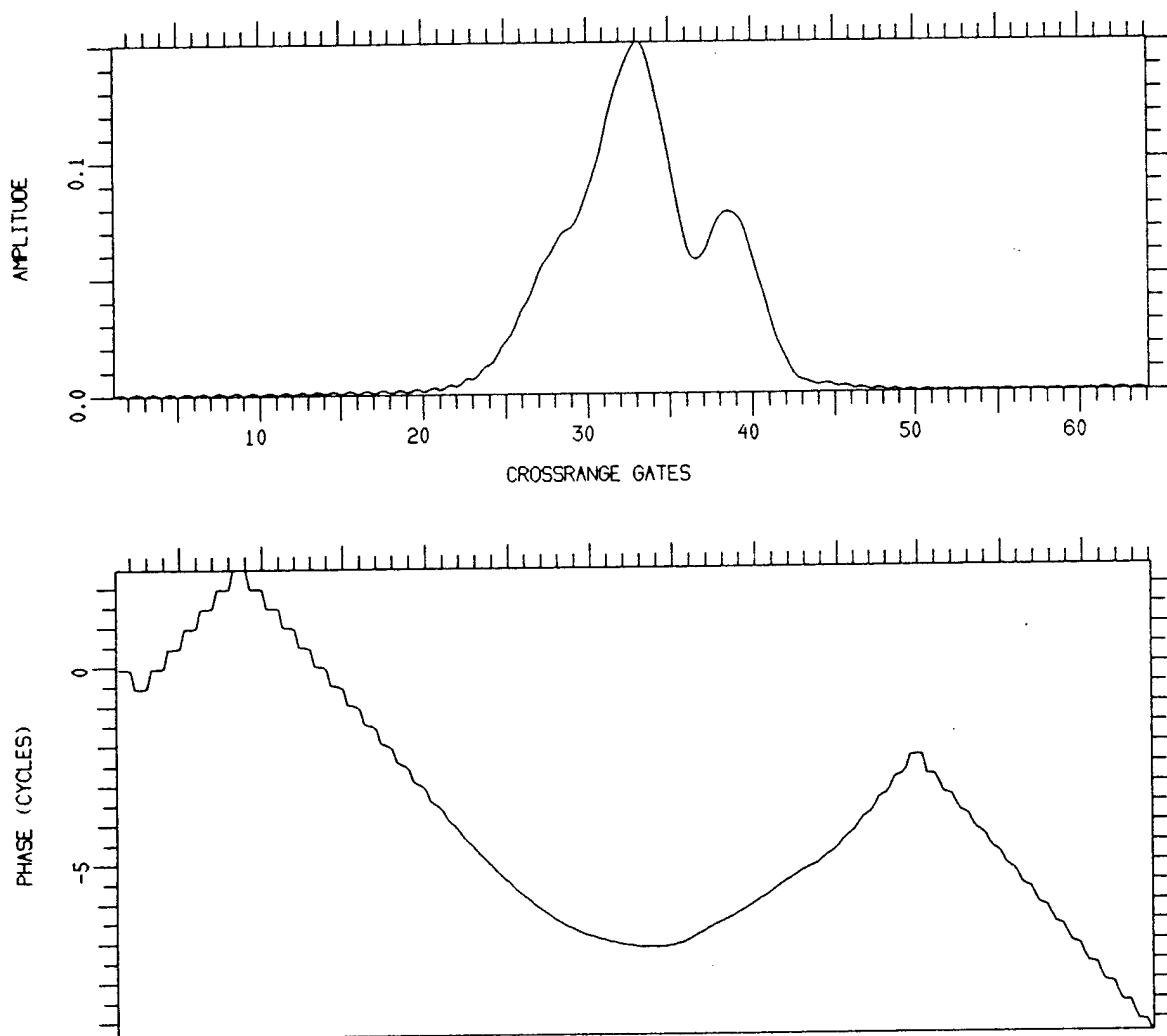


Figure A.1. Simulated Scatterers at Crossranges 33 and 36, Including Uncompensated Motion.

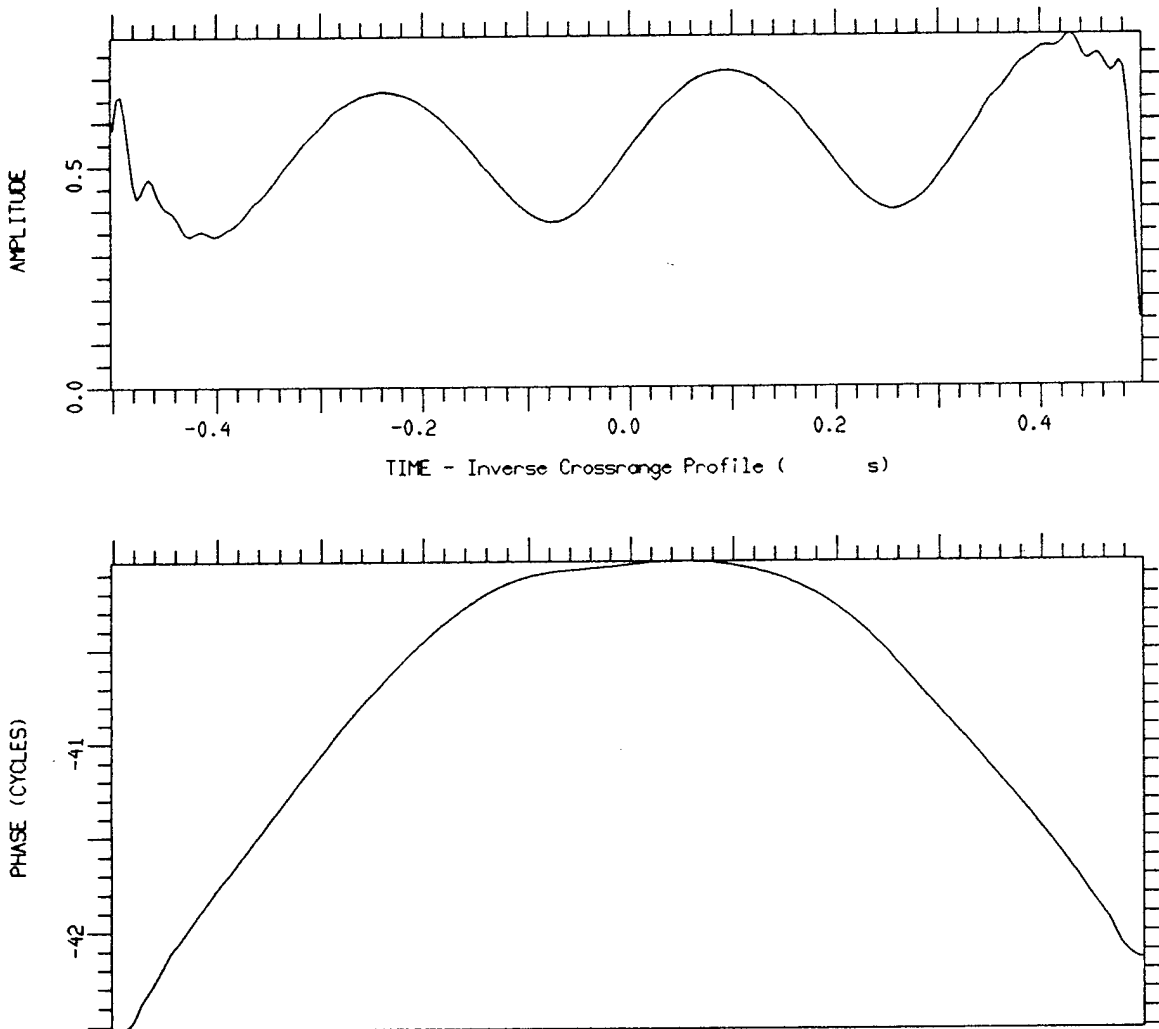


Figure A.2. Signal Corresponding to Figure A.1.

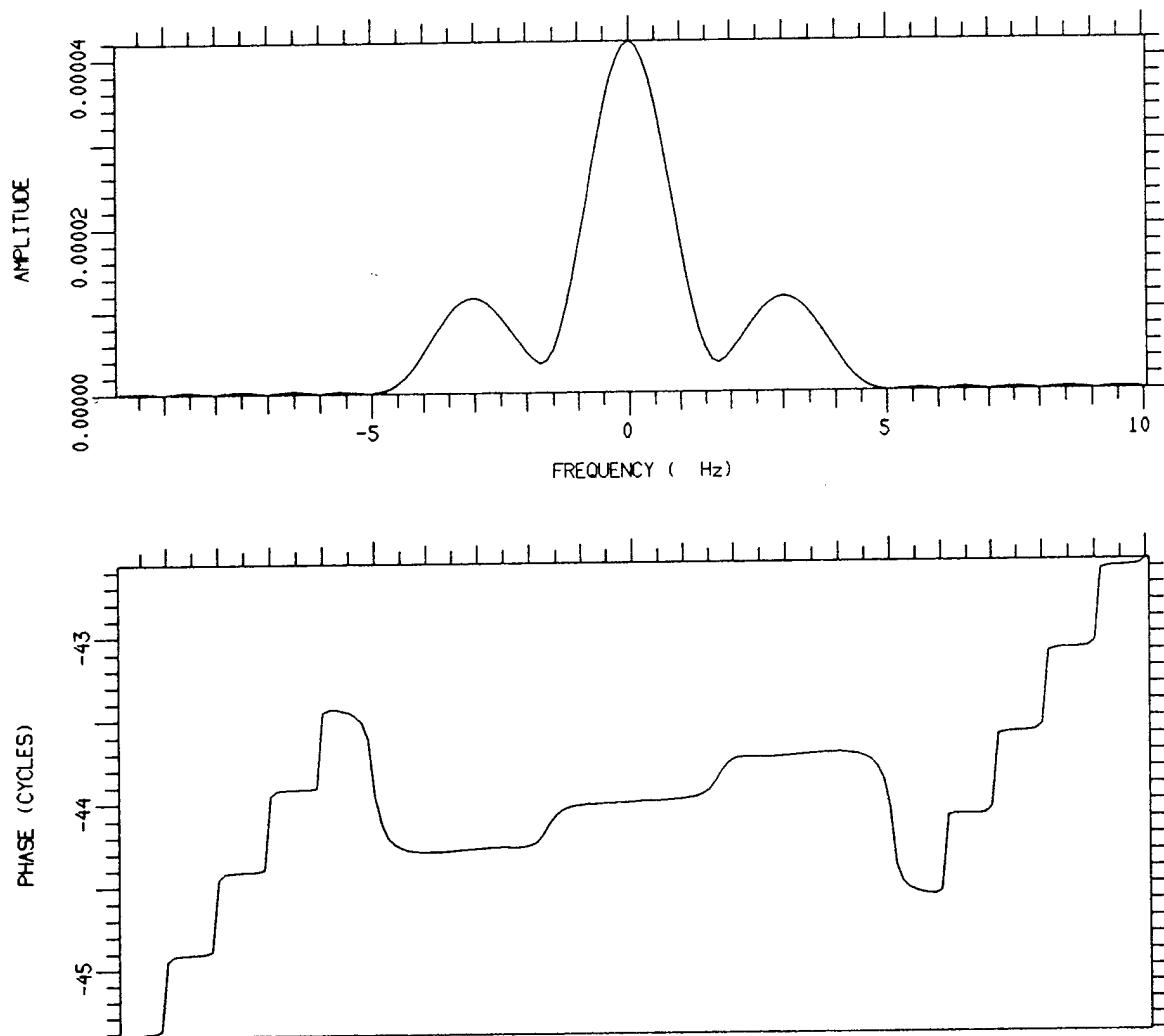


Figure A.3. Transform of the Power of Figure A.2.

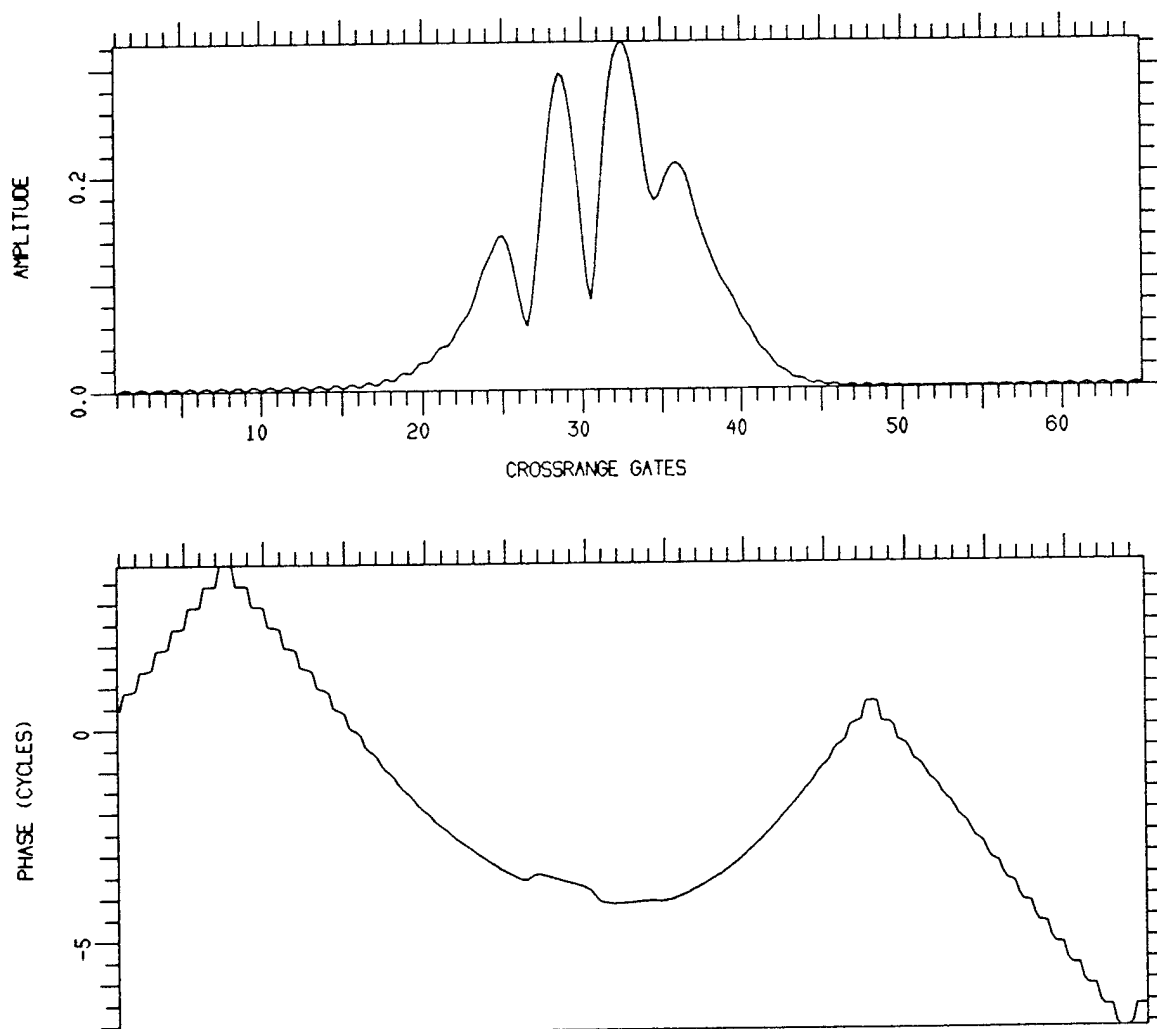


Figure A.4. Simulated Scatterers at Crossranges 33 and 28,
Including the same Uncompensated Motion of Figure A.1.

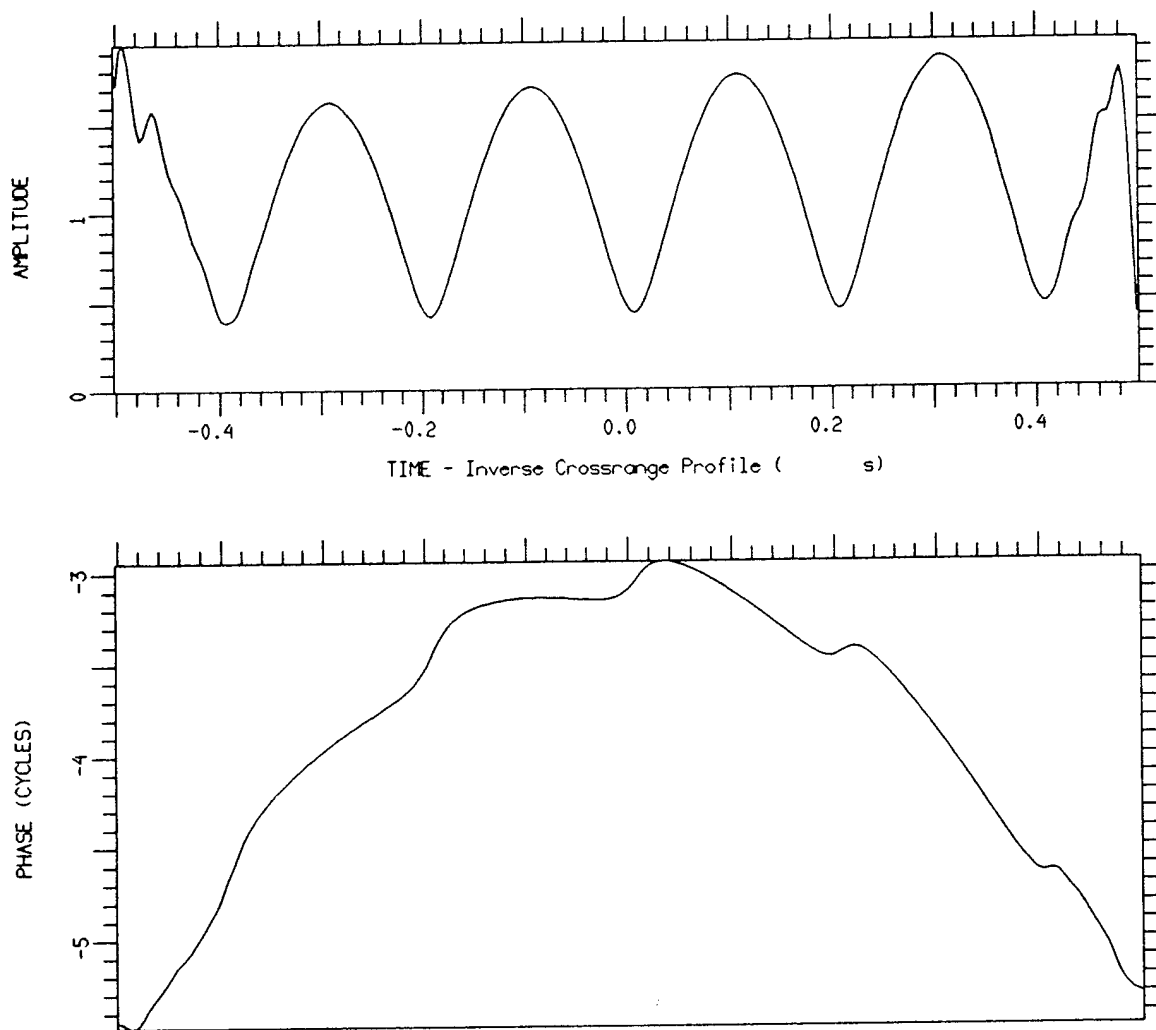


Figure A.5. Signal Corresponding to Figure A.4.

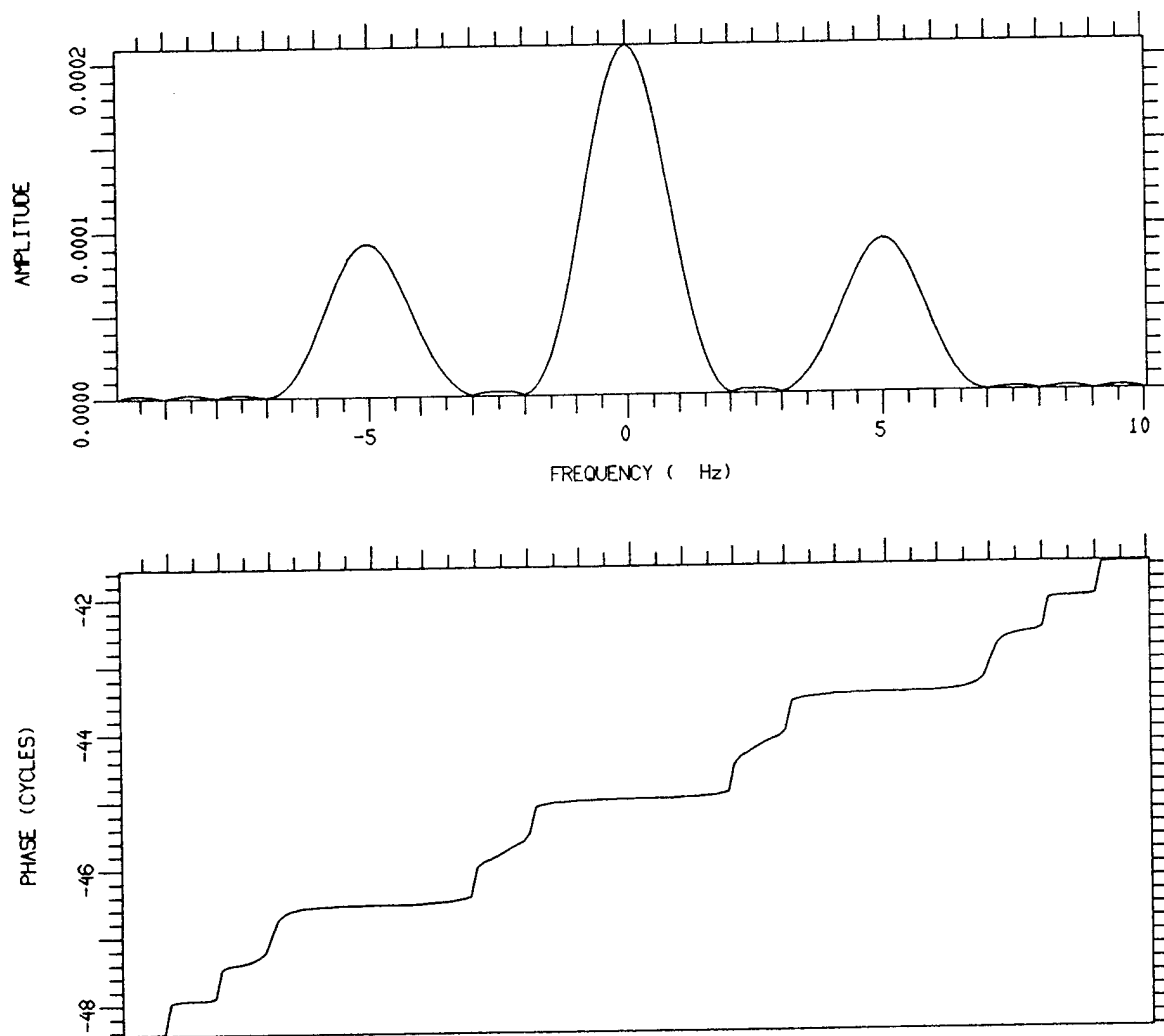


Figure A.6. Transform of the Power of Figure A.5.

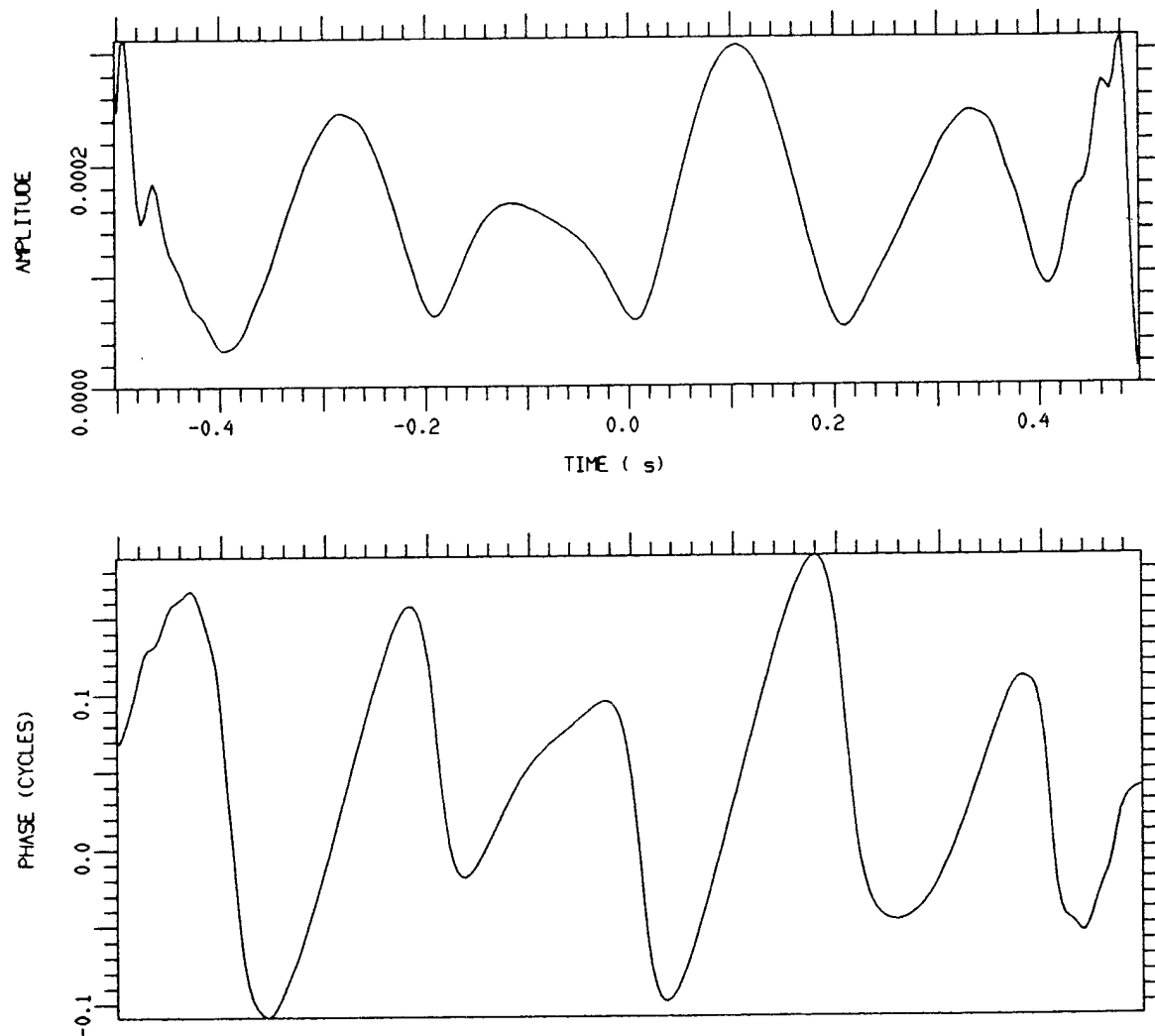


Figure A.7. Product of Signal of Figure A.2 and Complex Conjugate of Signal of Figure A.5.

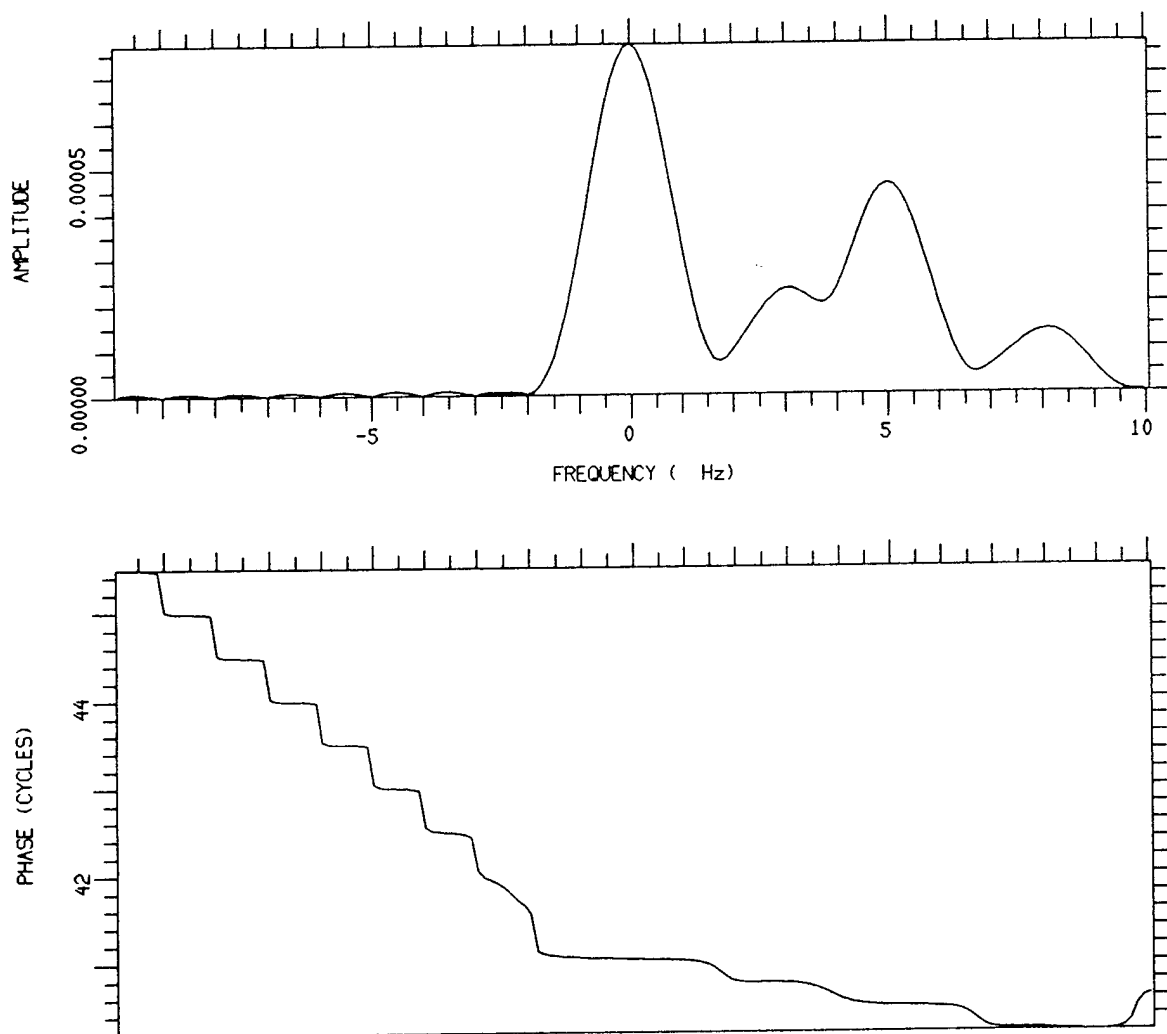


Figure A.8. Transform of Figure A.7.

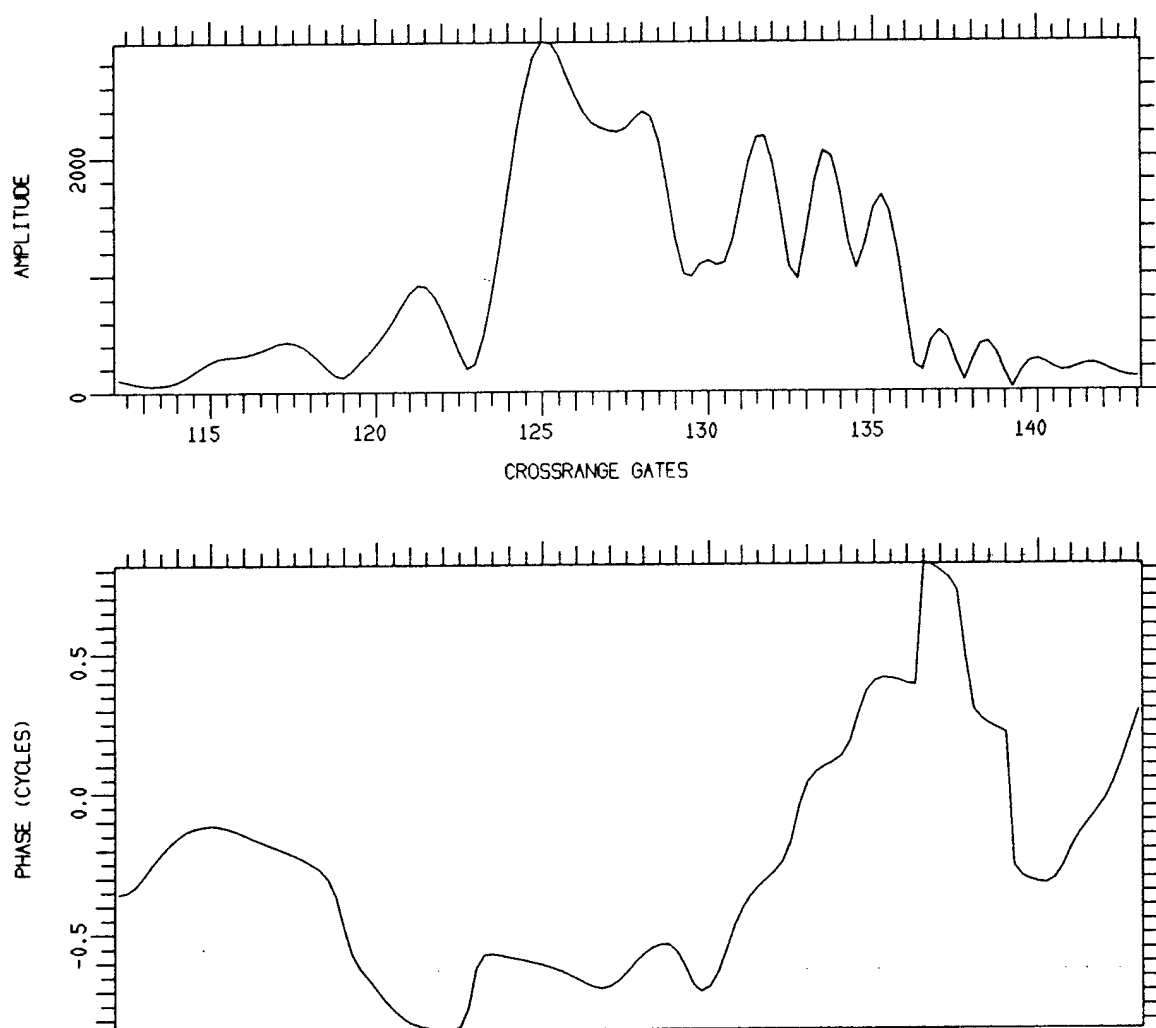


Figure A.9. Image Cut in Range Gate 33 of Figure 4.1.

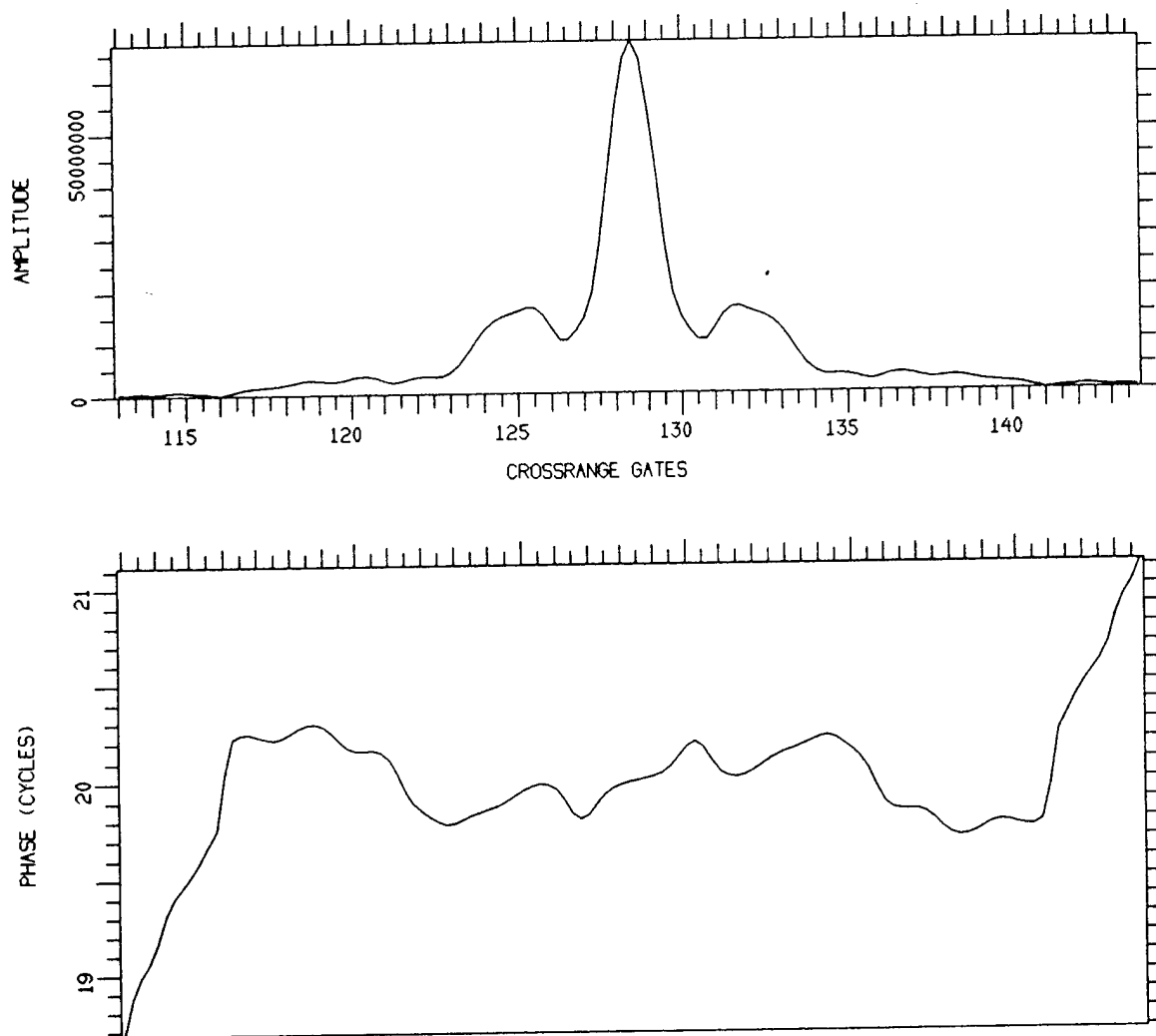


Figure A.10. Transform of the Power of the Signal
Corresponding to Figure A.9.

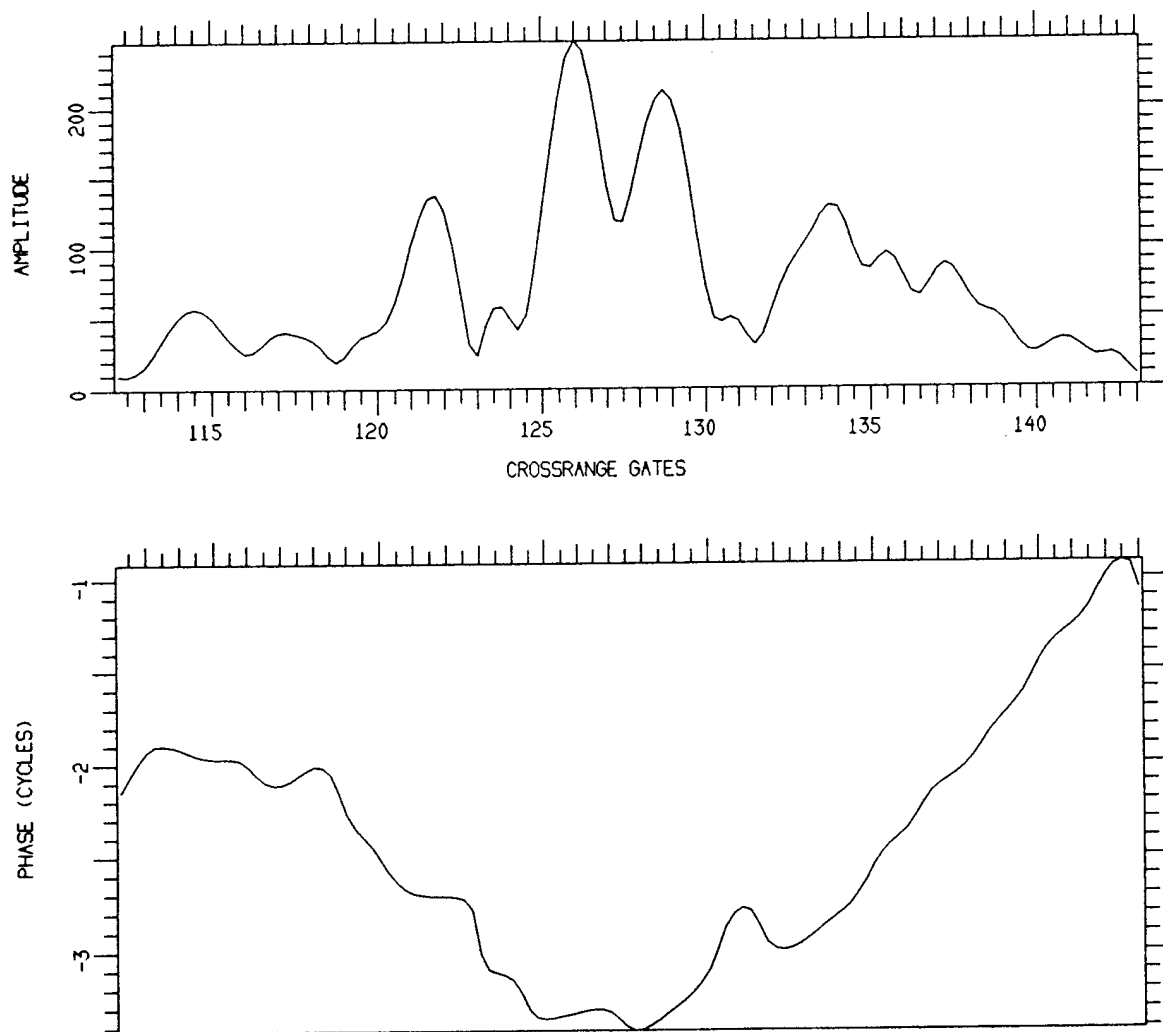


Figure A.11. Image Cut in Range Gate 35 of Figure 4.1.

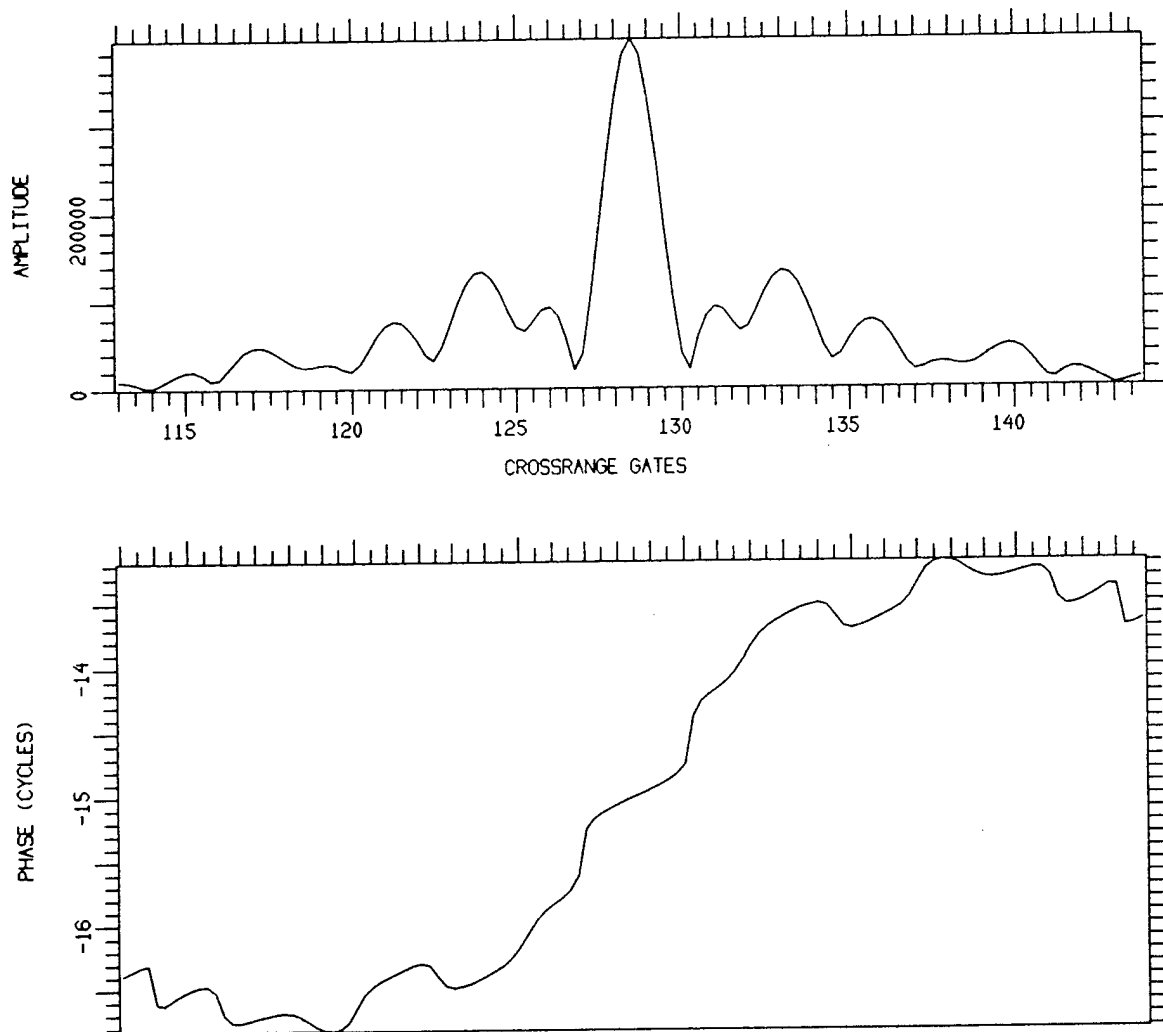


Figure A.12. Transform of the Power of the Signal Corresponding to Figure A.11.

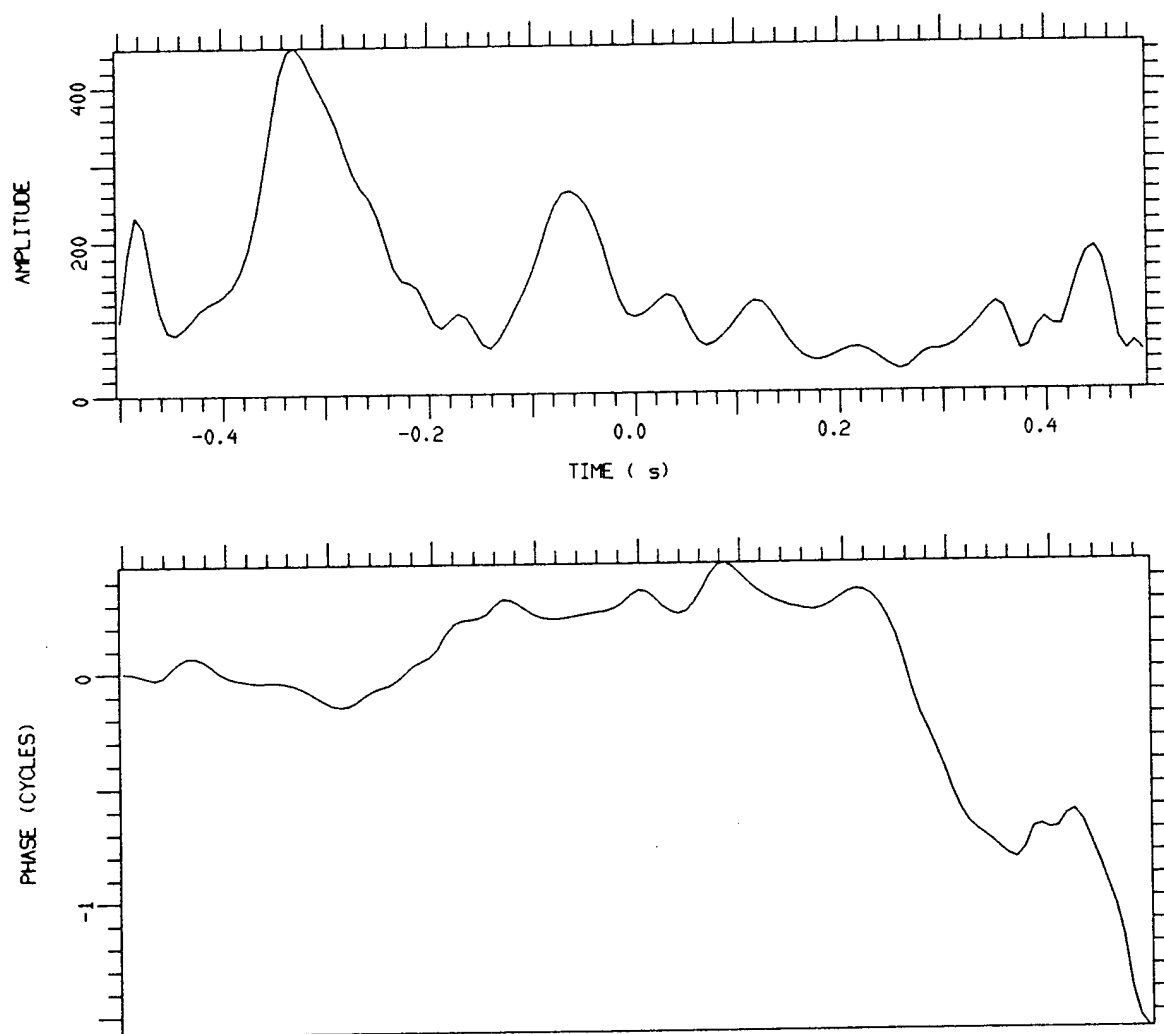


Figure A.13. Product of Signal of Gate 33 and Complex Conjugate of Signal of Gate 35.

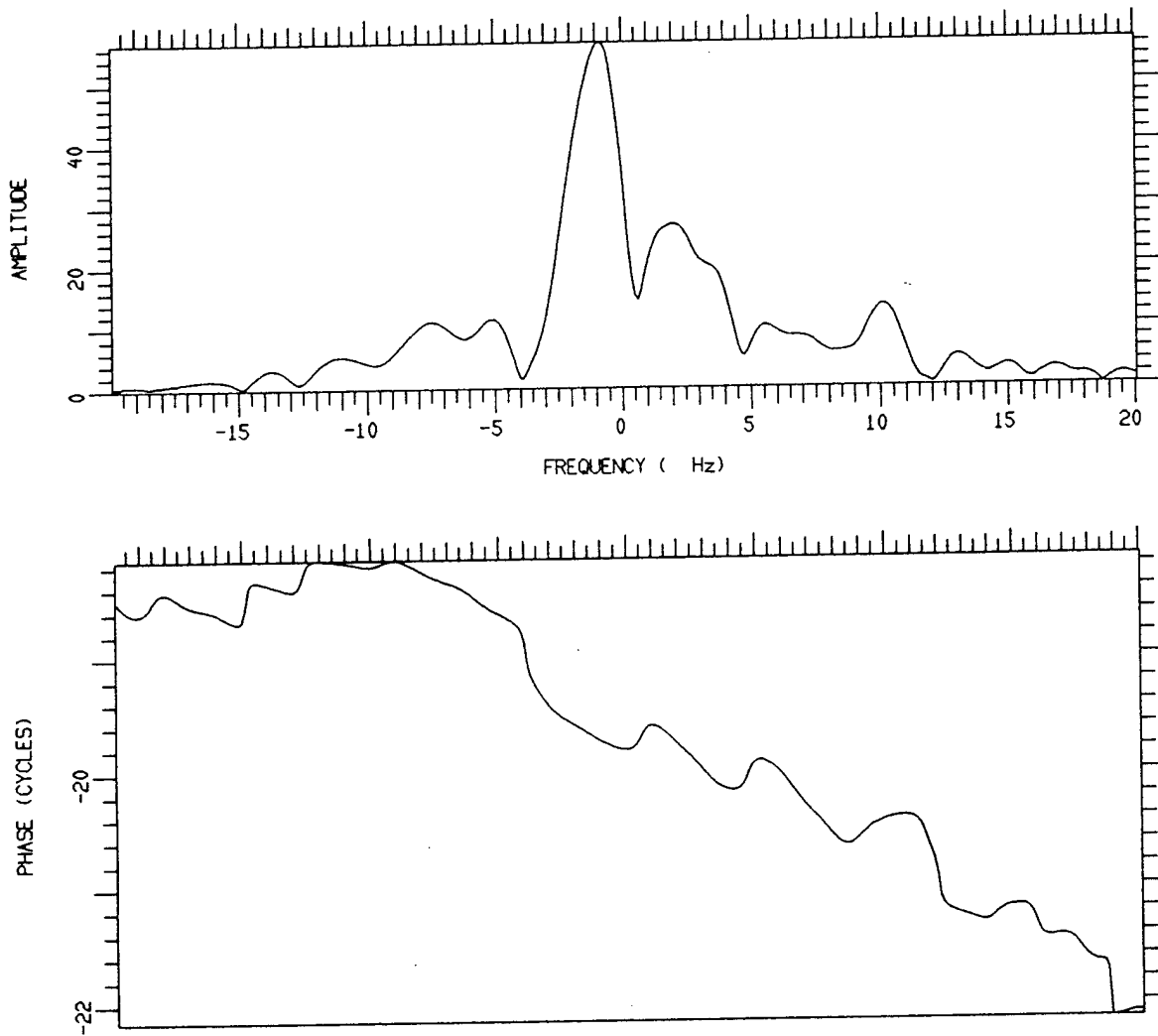


Figure A.14. Transform of Figure A.13.